

- High Energy Astrophysics: Terminology and Questions -

NOAJ Astrophysics Lecture Series, November 2013

**Introduction to Observational Nuclear Astrophysics
Lecture #1**

by Roland Diehl

Lecture Series Overview

- “Nuclear Astrophysics”

- ☞ **Nuclear Physics:**

- Description of Nuclear Forces
 - Properties of Atomic Nuclei

- ☞ **Astrophysics**

- Description of the Objects in the Universe
 - Description of Cosmological Evolution

- “Observations”

- ☞ **Collecting Measurements to Test & Constrain Theoretical Descriptions**

- Our place in the cosmos
 - Information from distant objects
 - » Radiation
 - » Materials

- This Lecture Set:

- ☞ **High-Energy Astrophysics and the Role of Nuclear Processes**
 - ☞ **Introduction to Nuclear Physics Processes in Cosmic Sites**
 - ☞ **Collecting Information about Cosmic Nuclear Processes**
 - ☞ **Special Instrumentation for Measurements of Cosmic Nuclear Processes**
 - ☞ **Recent Lessons about Stars, Supernovae, and Interstellar Gas**

Lecture Program

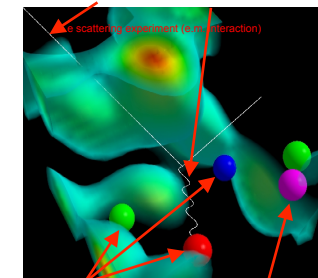
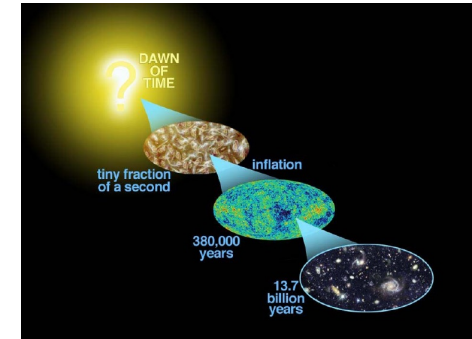
- 1: High-energy astrophysics: terminology and questions
- 2: Nuclear astrophysics: basic theory
- 3: Nuclei and cosmic nucleosynthesis; e^+ annihilation
- 4: Instruments measuring X-, gamma-, and cosmic rays
- 5: Stars and supernovae
- 6: Interstellar gas in galaxies

 *...adjusted as we proceed*

Astro-Physics Issues

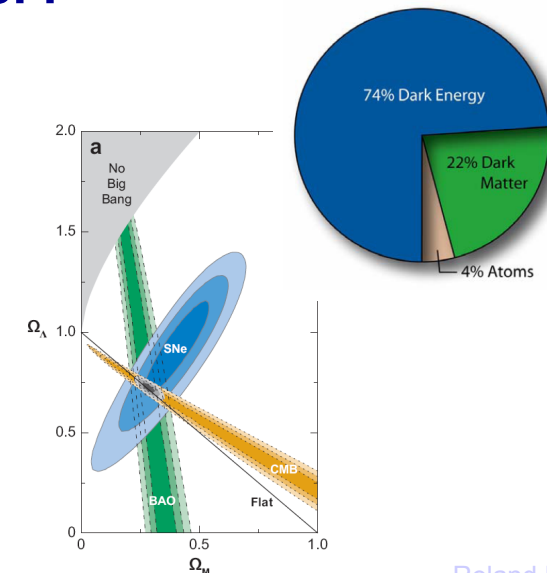


- ☆ **Current Models (SM) Successfully Describe Physics at Readily-Accessible Scales**
- ☆ **Why is the Standard Model so Complex (origin of mass)?**
- ☆ **Why does Weak Interaction Violate Parity?**
- ☆ **Why do Neutrinos have a Mass?**
- ☆ **Why Does Matter Dominate over Antimatter?**
- ☆ **What is Gravity?**
- ☆ **What is Dark Matter Composed of?**
- ☆ **Is our View of the Universe Even-More Incomplete? (dark energy?)**



valence quarks as confined by gluon field

virtual quark-antiquark pair from gluon field



What is High-Energy Astrophysics?

- “High Energy” = ...
 - ★ Energy Scale of the Astrophysical Process
 - ★ Energy Regime of the Cosmic Messenger
- Relative Definition,
→ look at ranges and scales

High-Energy Astrophysics

☆ Viewpoints for a Possible Definition:

☞ Typical Cosmic Objects and their Characteristic Observational Signatures

- » Stars&Galaxies/thermal to UV; AGN/radio to Gamma;
Explosions/HE-Gamma to Radio; DM/??

☞ Typical Astronomical Messengers and their Characteristic Sources

- » Spectral Lines: dust-molecules-atoms-nuclei-nucleons; CR: ??; n: explosions

☞ Physical Processes to Generate High-Energy Particles & Photons

- » X: Bremsstrahlung; g: radioactive decay; HE-g: p, CR's

☆ Some Classification Criteria:

☞ What is the high-energy end of common instrumentation?

- » Grazing-incidence mirrors

☞ What is the high-energy end of familiar physics?

- » relativistic particles and their radiation; nuclear and elementary-particle physics

☞ What are the low and high energy extremes of imaginable sources?

- » cold dust in space / few K $\leftarrow \rightarrow$ GRBs (photon pressure > gravitational pressure)

☞ Which physical processes are different at high wrt. low energies?

- » photon interactions with matter: Wave/particle dualism
- » particle interactions: changes of internal energies

About "Energy"

★ Defining Energy

- ☞ Thermodynamical System Variable
- ☞ Defined from Symmetry in Time
- ☞ Zero Point?
- ☞ deBroglie Wavelength: Where Diffraction Starts...

★ Rest Mass and Kinetic Energy

- ☞ Low Energy = Where Kinetic Energy is Smaller than Rest-Mass Energy
- ☞ High Energy = Where Kinetic Energy is Greater than Rest-Mass Energy

★ Units

- ☞ Joule, erg, eV:
 - $1 \text{ MeV} = 1.6022 \cdot 10^{-13} \text{ Wsec (=J)} = 4.505 \cdot 10^{-20} \text{ kWh} = 1.6022 \cdot 10^{-6} \text{ erg}$

★ Sources of Energy

- ☞ Chemical
 - $1 \text{ kg wood} = 2.0 \cdot 10^7 \text{ J} ; \quad 3.2 \cdot 10^7 \text{ J} = 1 \text{ l gasoline}$
- ☞ Nuclear
 - $1 \text{ kg H to He} = 1.0 \cdot 10^{15} \text{ J} = 31,320,000 \text{ l gasoline}$
- ☞ Gravitational
 - $1 \text{ kg onto NS} = 1.3 \cdot 10^{16} \text{ J} = 415,000,000 \text{ l gasoline}$

Energy Scales



★ Rest-Mass Energy

- ☞ **Energy Equivalent of Mass**
 - Main Matter Constituents

$$E = mc^2$$

$$E_{tot} > mc^2 \Leftrightarrow \text{relativistic}$$

$$E = N \cdot m_i c^2$$

$$m_e c^2 \approx 0.5[MeV]$$

$$m_p c^2 \approx 1[GeV]$$

★ Thermal Energy

- ☞ **Kinetic-Energy Distribution**
 - Typical Thermal Energy:

$$\mathcal{E} \approx k_B T$$

$$k_B = 8.6132 \cdot 10^{-11}[MeV / K]$$

★ Gravitational-Binding Energy

- ☞ **Gravitational Potential Energy**
 - Gravity total (N particles):

$$E_{grav} \approx \frac{G \cdot (Nm_i)^2}{R}$$

$$G = 6.6726 \cdot 10^{-8}[cm^3 g^{-1} s^{-2}]$$

$$E_{Grav, NS} \approx 200 \left[\frac{10km}{R} \right] \left[\frac{mc^2}{1GeV} \right] [MeV]$$

★ Atomic-Binding Energy

- ☞ **Electromagnetic Potential Energy**
 - Coulomb Potential Energy:

$$a_0 = \hbar^2 / m_e q^2$$

$$E_C \approx \frac{m_e \cdot q^4}{2\hbar^2} \approx 13.6[eV]$$

★ Molecular-Binding Energy

- ☞ **Electromagnetic Potential Energy (net charge)**
 - Oscillations within Potential Well of $\sim E_C$

$$E_{vib} \approx \left(\frac{m_e}{\mu} \right)^{1/2} \cdot E_C \approx 0.25[eV]$$

$$E_{rot} \approx \left(\frac{m_e}{\mu} \right) \cdot E_C \approx 10^{-2}[eV]$$

★ Nuclear-Binding Energy

- ☞ **Nuclear Potential Energy**
 - Nucleon Binding

$$r_0 \approx 1fm$$

$$E_C \approx \frac{m_p \cdot q^2}{1fm} \approx 1[MeV]$$

Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?

★ Nuclear Energy Release

- Structure of Stars
- Dynamics of Explosions

★ Nucleosynthesis

- Elemental Abundances in Stars and ISM (SNR), IGM
- Radioactive Isotopes

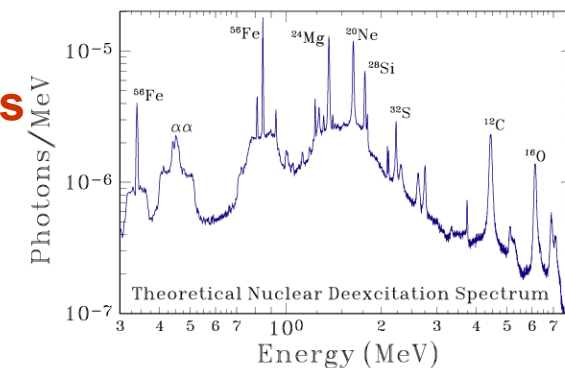
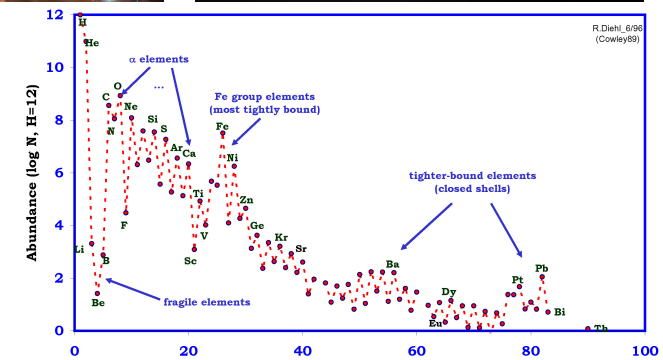
★ Characteristic Nuclear Radiation

- Nuclear Excitation (Emission/Absorption Lines)
- Radioactive Decay

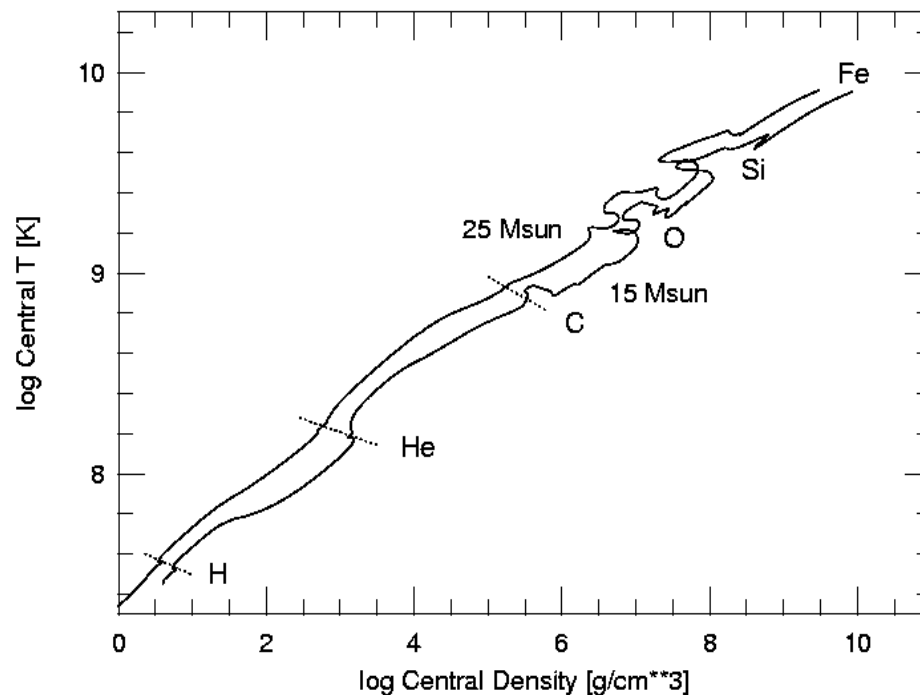
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👉 Nature of Cosmic Sources, Cosmic Processes

👉 Search for New Phenomena



What is a massive star?



Stars are gravitationally confined thermonuclear reactors

Each time one runs out of one kind of fuel, contraction and heating ensue, unless degeneracy is encountered.

For a star over $8 M_{\odot}$ contraction and heating continue until a Fe core is made

Gravitational collapse ensues, after no energy-providing fuel is left

courtesy SEWoosley

Branches of Stellar Evolution

★ Total Mass Determines

- ☞ Ignition of Nuclear Fuel (Temperature, from Gravitational Compression)
- ☞ Degeneracy of Electrons in Core (Size of Core)

★ Physical Processes which Shape Stellar Evolution:

- ☞ Nuclear Burning
- ☞ Mass Loss

★ Low-Mass Stars [$M < 2.3 M_{\odot}$]

- ☞ Ignition of H
- ☞ He Core Becomes Degenerate Before Ignition

★ Intermediate-Mass Stars [$3 M_{\odot} < M < 8 M_{\odot}$]

- ☞ Ignition of H, He, C, O
- ☞ White Dwarf Remnant

★ High-Mass (Massive) Stars [$M > 8 \dots 11 M_{\odot}$]

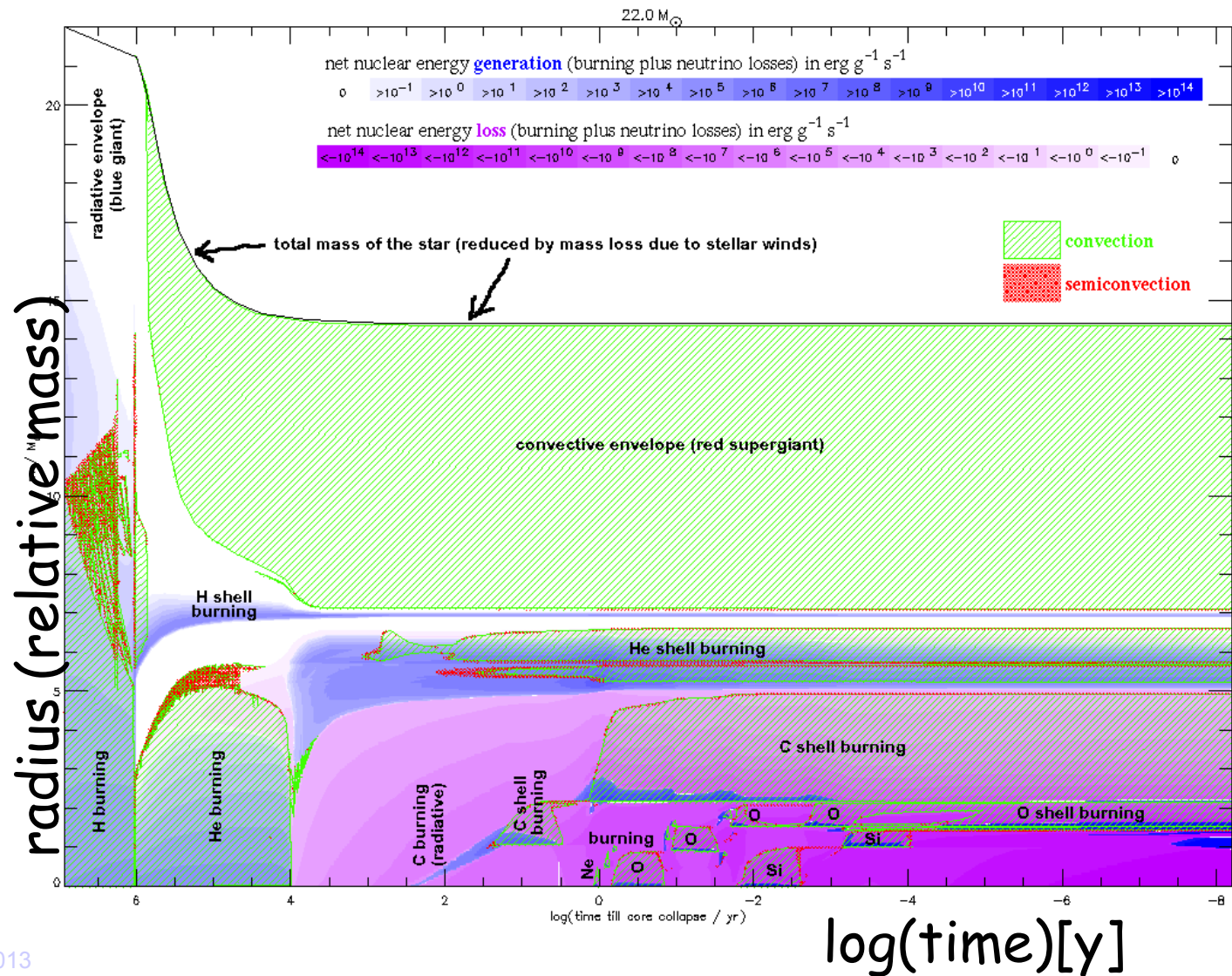
- ☞ Ignition of H,...Si
- ☞ Core Collapse Supernova, NS or BH Remnant

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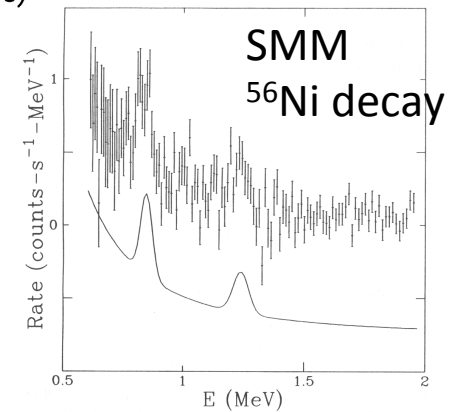
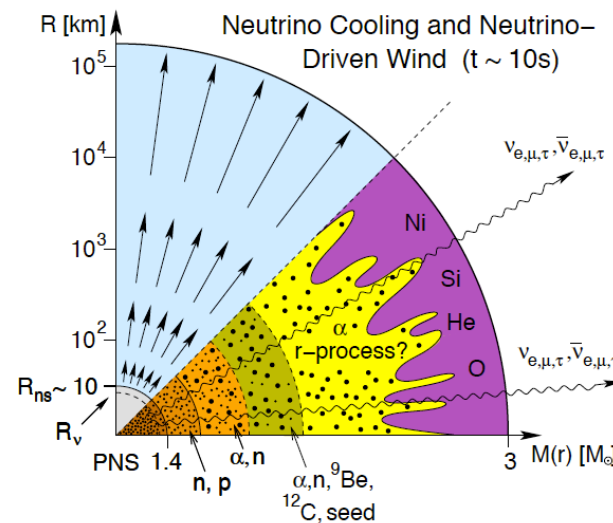
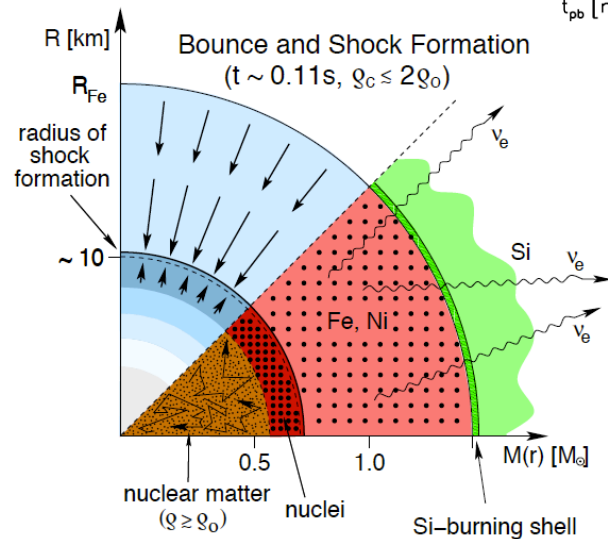
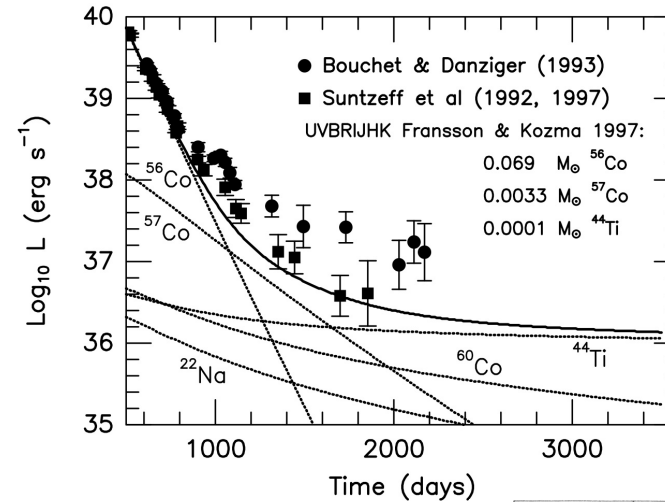
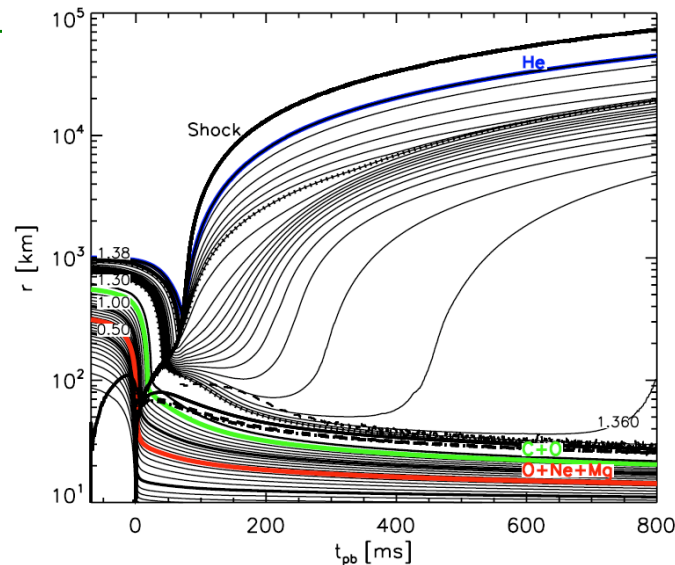


Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?

★ Nuclear Energy Release

– Dynamics of Explosions

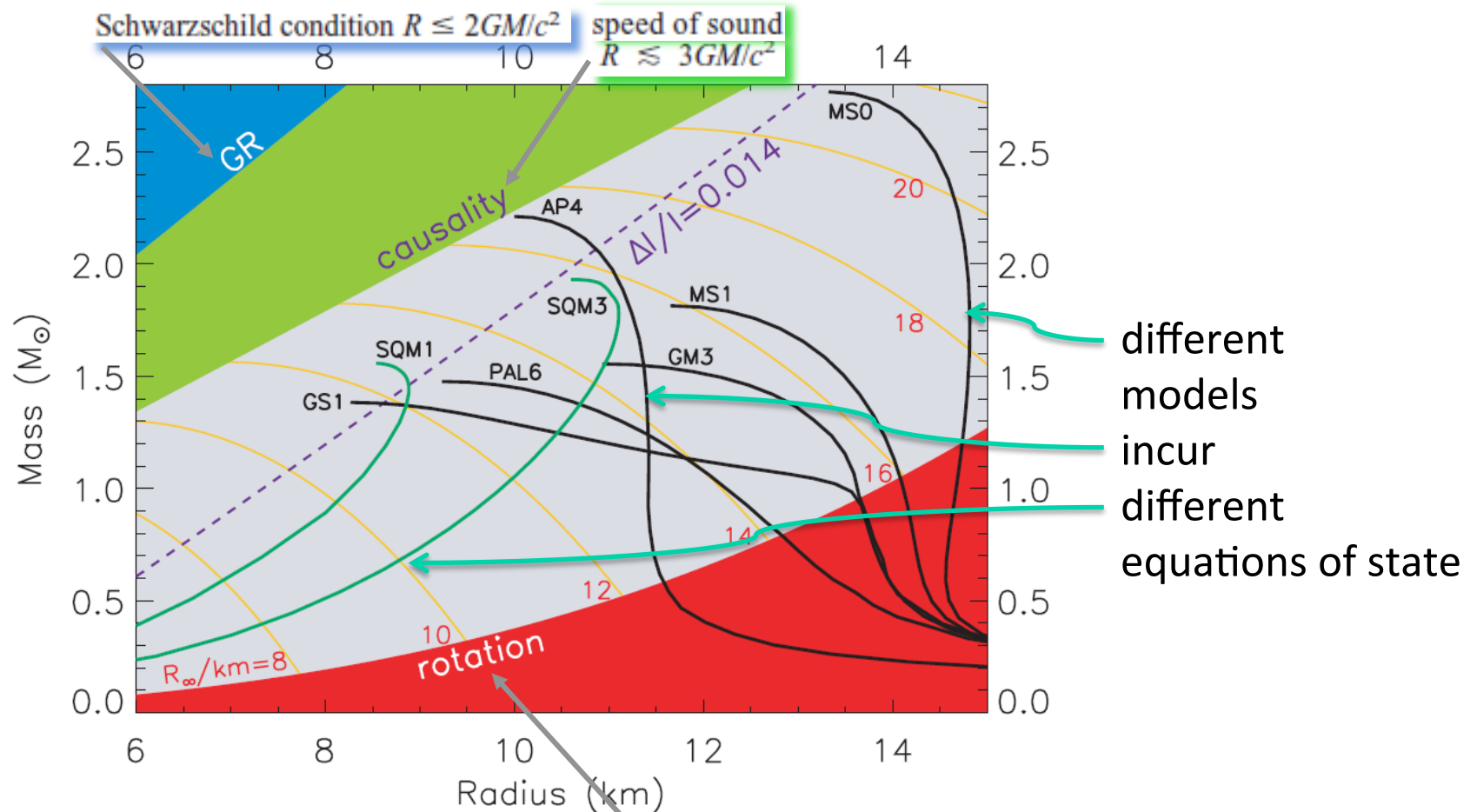


Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?

Structure of Neutron Stars

→ Mass-Radius Relation ↔ Composition & State of High-Density Matter

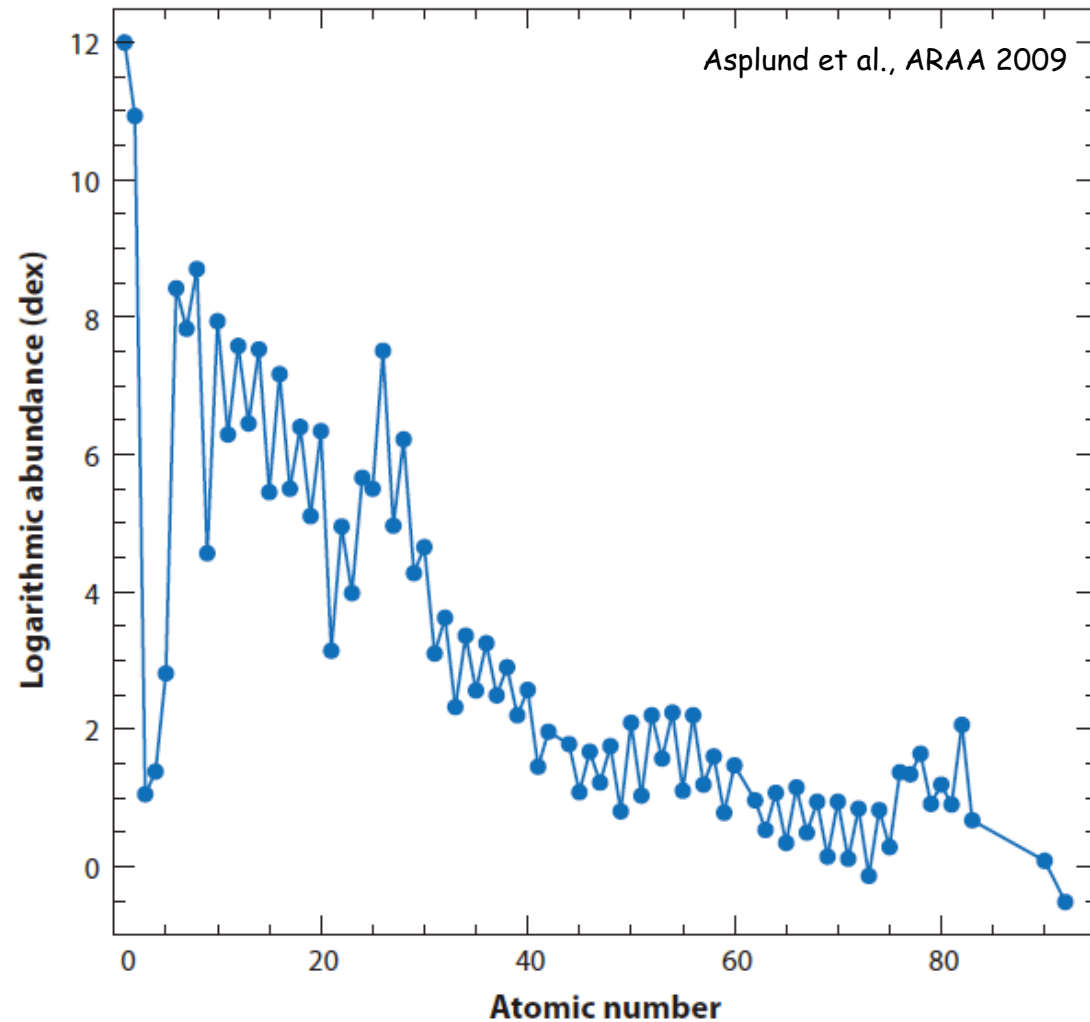


$$v_K = (2\pi)^{-1} \sqrt{GM/R^3} = 1833 (M/M_{\odot})^{1/2} (10 \text{ km}/R)^{3/2} \text{ Hz}$$

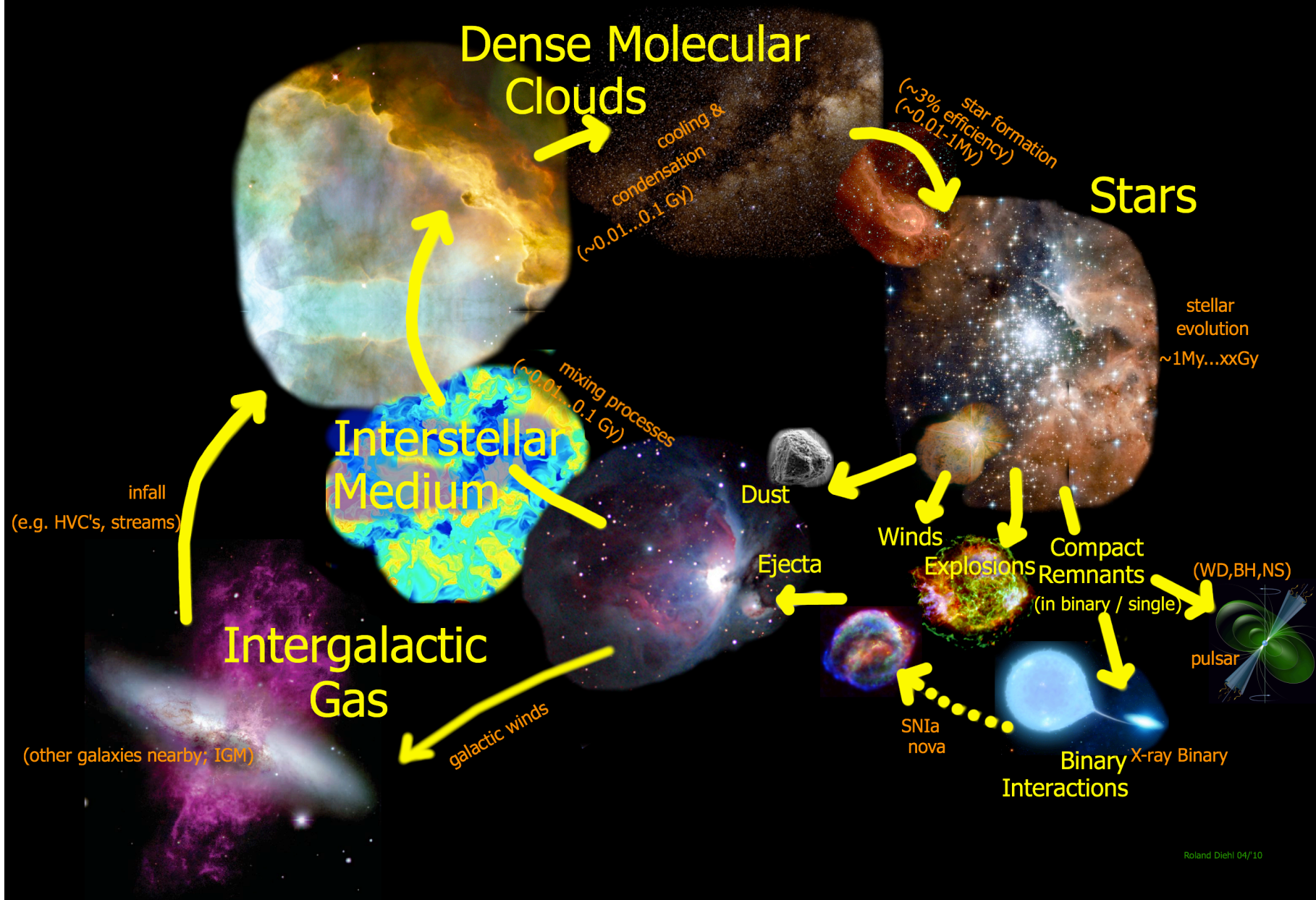
The Quest: Origin of the Elements

☆ What is the Origin of the Variety of Cosmic Elements...

- ☞ at its presently-observed variety (here: solar)
- ☞ with abundances spanning 12 orders of magnitude,
- ☞ ... and revealing remarkable sub-structure

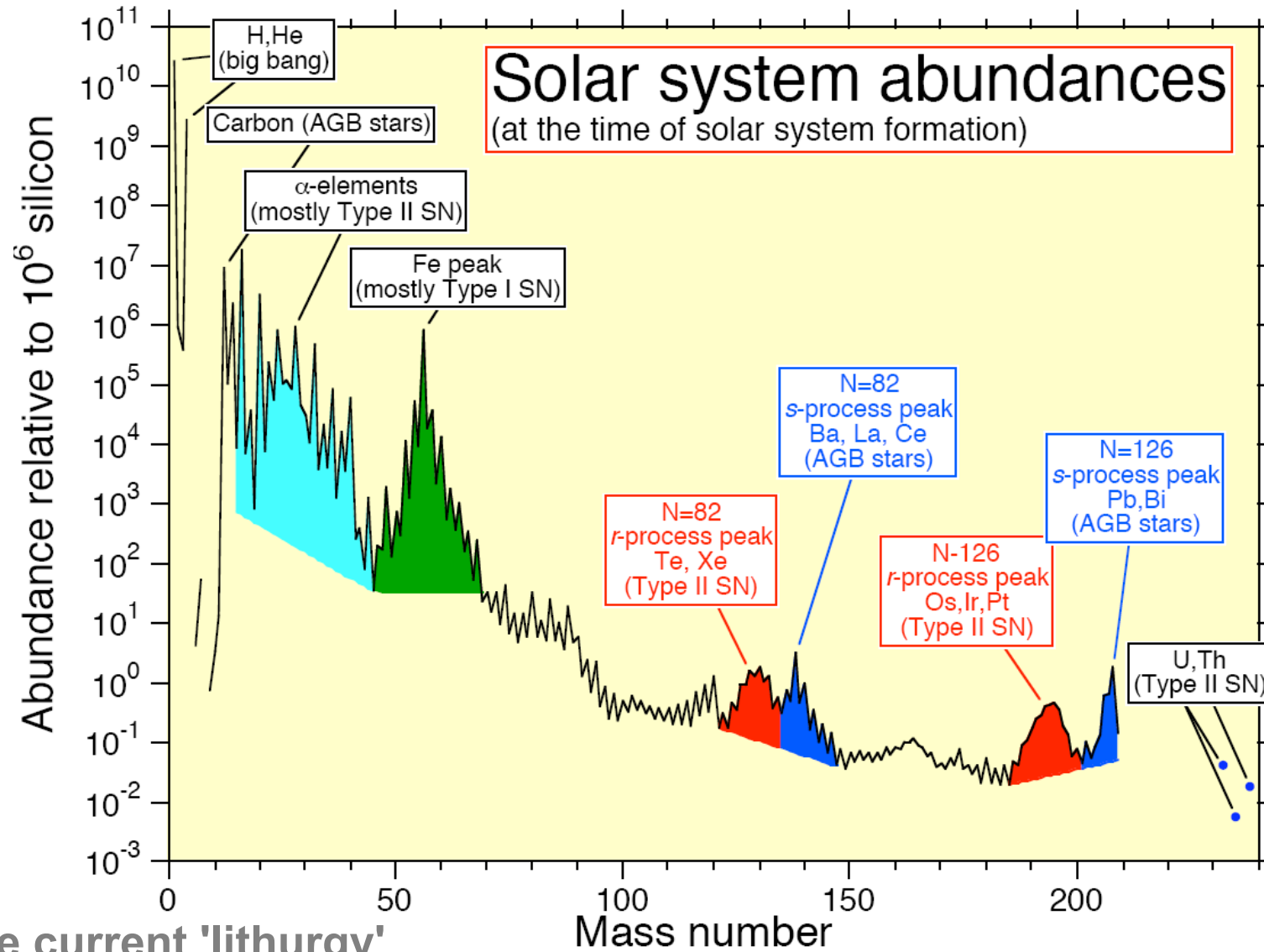


Cosmic Cycles of Matter



Roland Diehl 04/10

One of the Key Tools of Astrophysics: Where do specific atomic nuclei and their abundance originate?



☆ ... the current 'lithurgy'
-> how much do we understand?

Courtesy: Andy Davis

Astrophysics and Nuclear Physics

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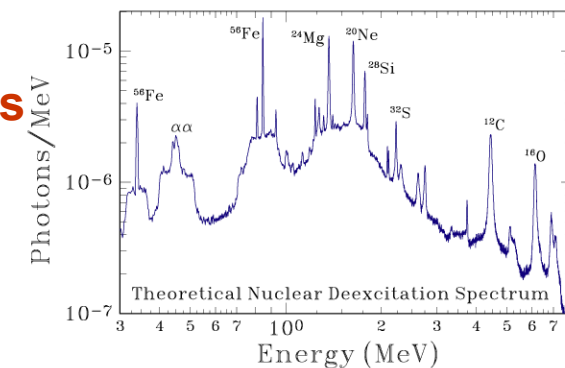
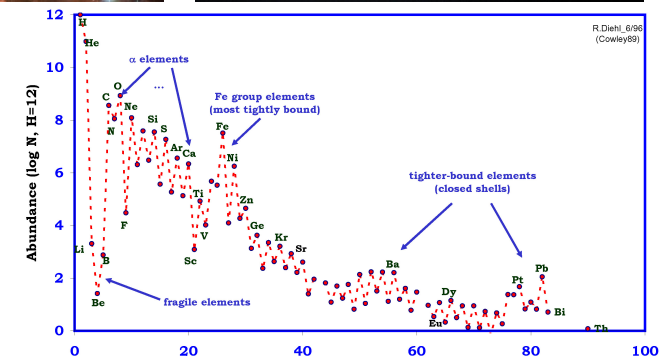
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=>

👉 Nature of Cosmic Sources, Cosmic Processes

👉 Search for New Phenomena



Key Nuclear-Physics Questions

- ☆ What is the Nature of the Nuclear Force, as it Binds Known Nuclei?
- ☆ What is the Origin of Simple Patterns found in Nuclear Structure?
- ☆ What is the Composition and Structure of Neutron Stars?
- ☆ What is the Origin of Cosmic Elements?
- ☆ What are the Nuclear Reactions that Drive the Evolution of Stars and Stellar Explosions?

 *adapted from Dean, PT 2007*

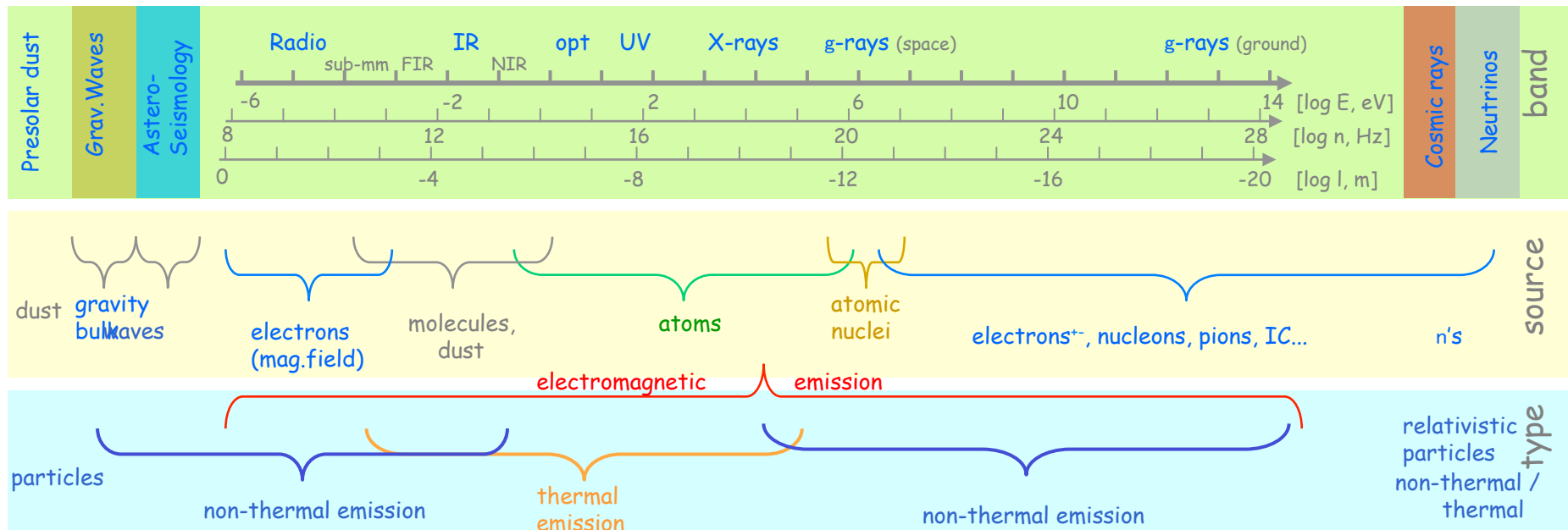
Messengers from Cosmic Objects

- “Radiation”

- ★ Electromagnetic
- ★ Cosmic Rays
- ★ Neutrinos
- ★ Waves

- “Matter”

- ★ Planets & Moon
- ★ Meteorites
- ★ Cosmic Dust
- ★ Cosmic Rays
- ★ Neutrinos



The Cosmos DOES Accelerate Particles!



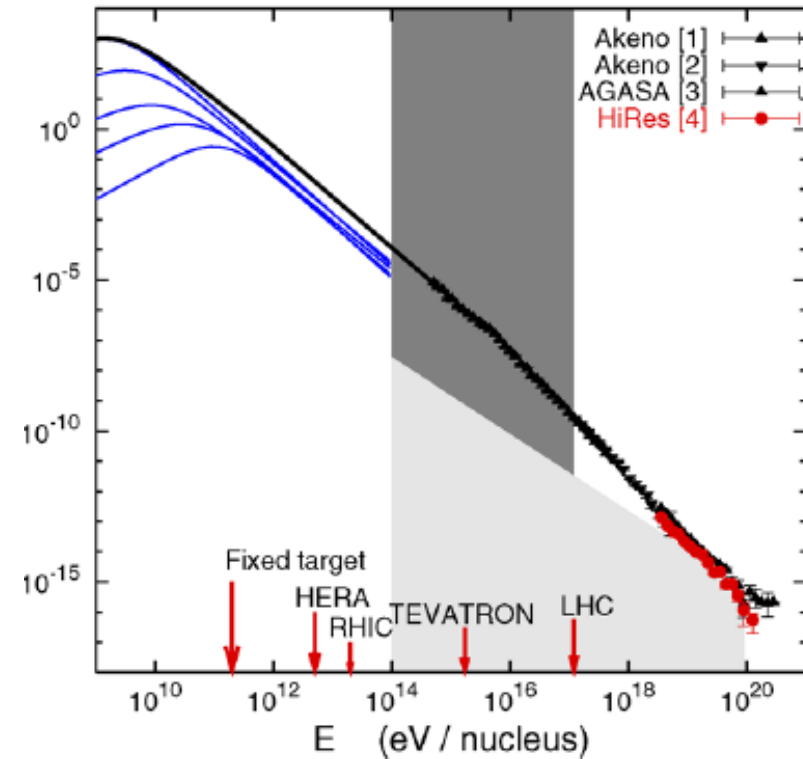
- Cosmic Rays up to 10^{21} eV
- ★ 1912-VICTOR HESS (Nobel Prize 1936)



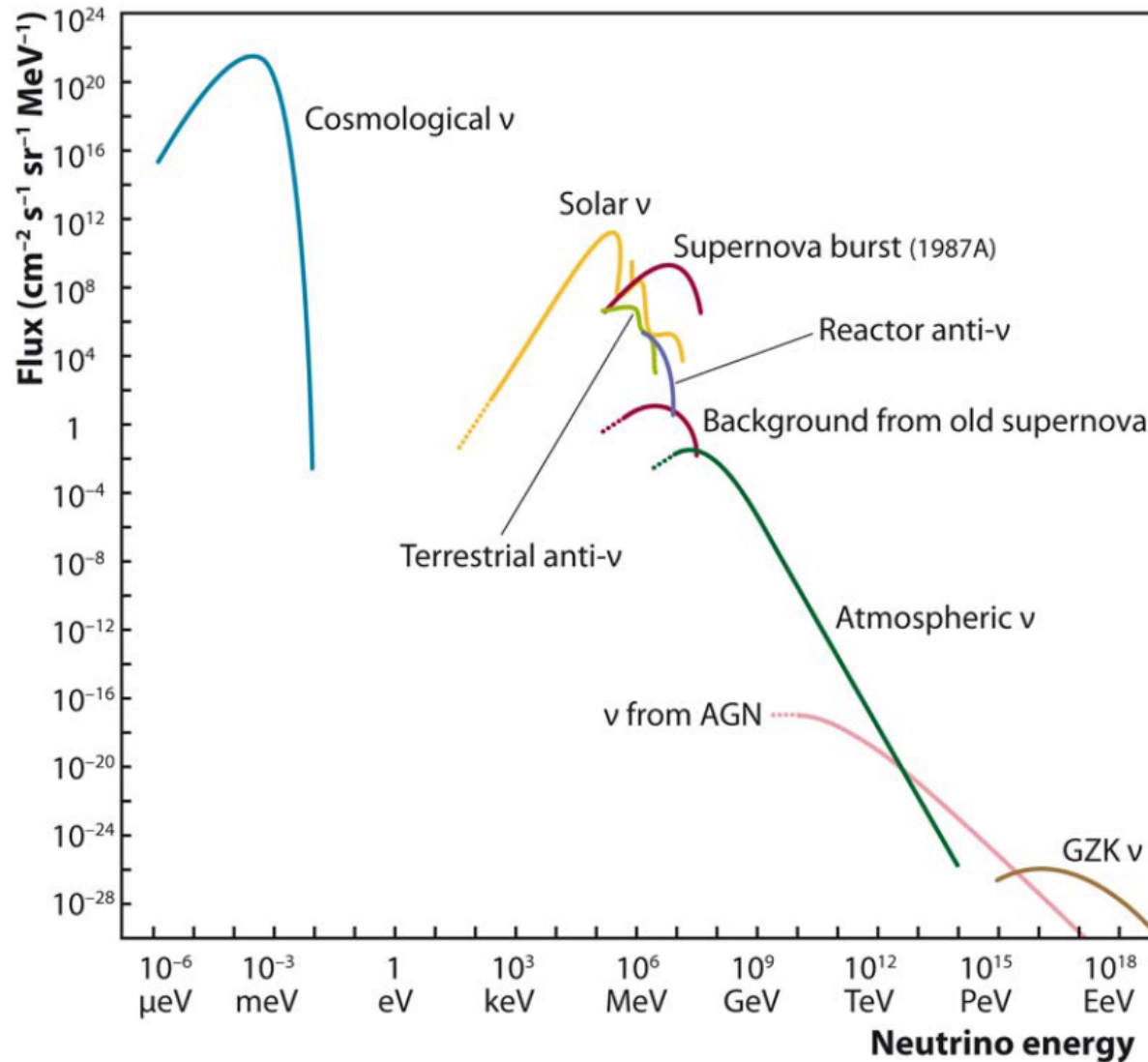
- **Balloon Flight Measurement of the “Höhenstrahlung” w. Ionisation Chamber**

- ☞ up to 2000 m decrease of ionisation (soil radioactivity)
- ☞ dramatic increase above! (Hess reached 5300 m)

➤ **Confirmation of extraterrestrial origin of "cosmic radiation"**



Neutrinos from Cosmic Sources



★ Cosmic Neutrinos

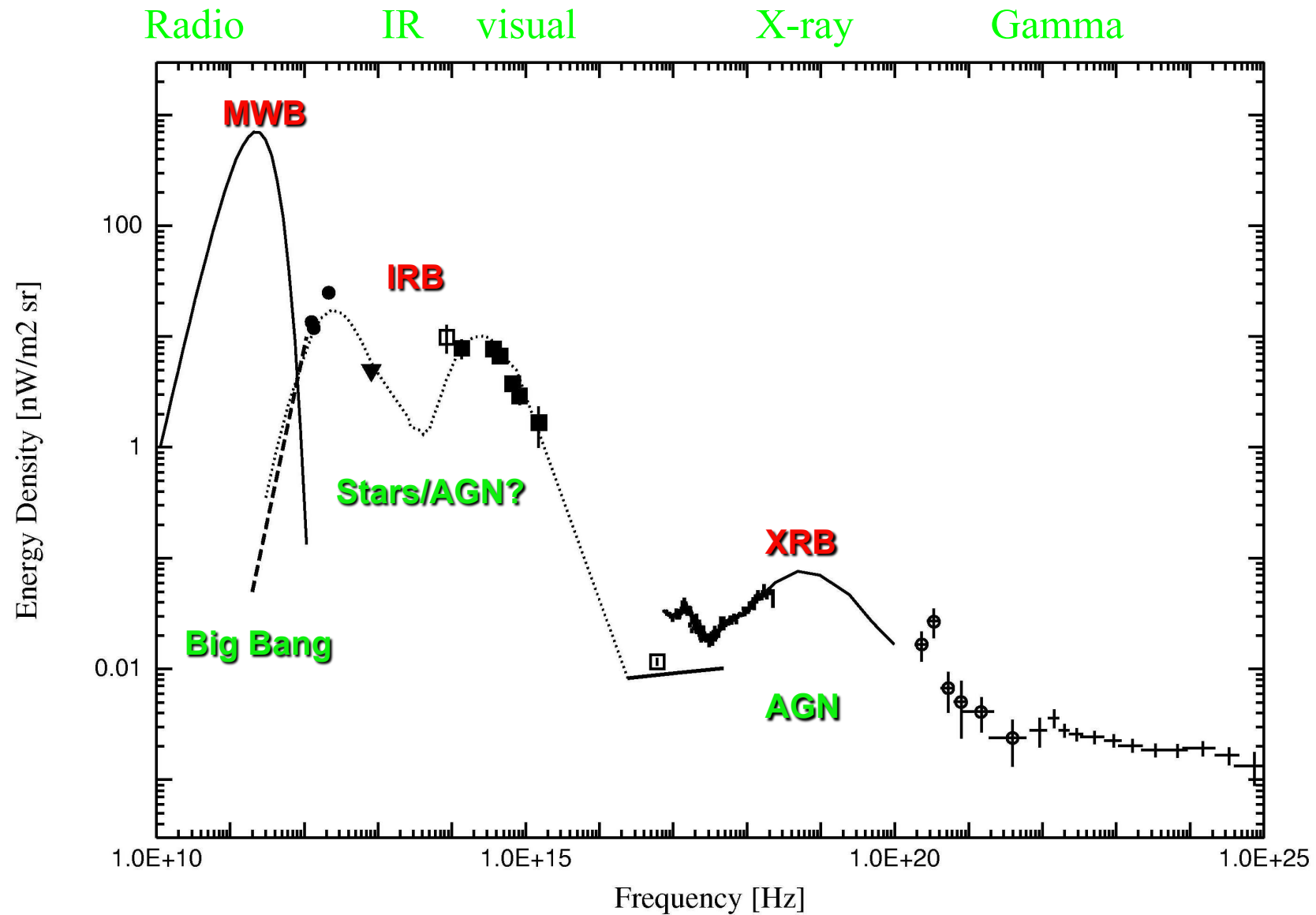
- from a Variety of Cosmic Sources
- Covering a Wide Energy Range

Cosmic Objects...



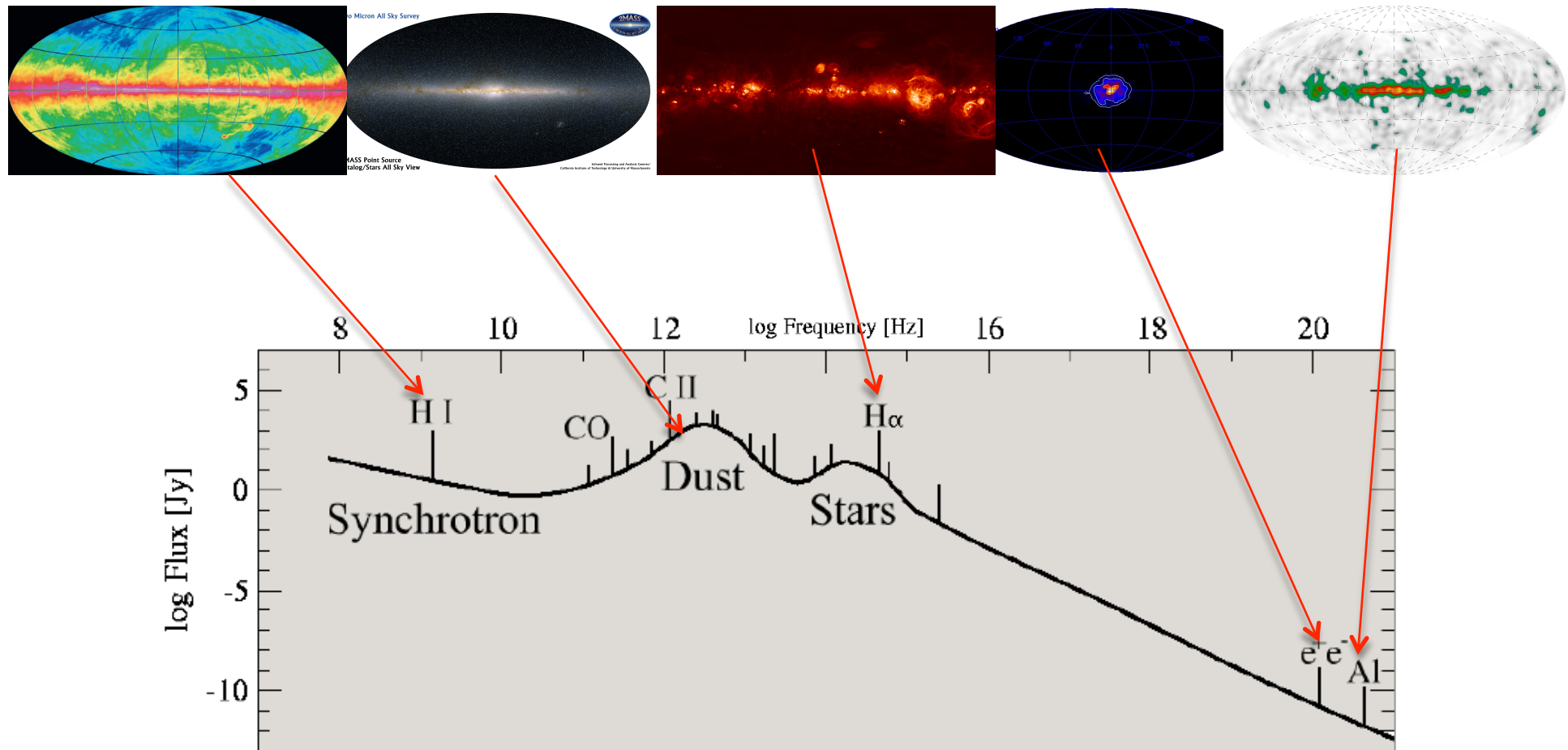
- **Stars**
 - ☞ Normal Stars
 - ☞ Flaring and Variable Stars
 - ☞ Compact Stars (WD, NS, BH)
 - ☞ Accreting Binaries
 - ☞ “Exploding” Stars (SN,N; GRB?)
- **Interstellar Medium**
 - ☞ Molecular Clouds, Neutral ISM
 - ☞ Ionized Regions
 - ☞ Supernova Remnants
 - ☞ Galaxy-IntraCluster Gas
- **Galaxies**
 - ☞ Normal Galaxies
 - ☞ Active Galaxies (Quasars, Blazars,...)
- **Large-Scale Structure of Universe**
 - ☞ Galaxy Clusters
 - ☞ Cosmic Microwave Background
 - ☞ Dark Matter

The Energy Spectrum of Diffuse Cosmic Radiation



Emission from Galaxies

☆ Normal Galaxies (Milky Way)



Stars: Typical Emission Signature

★ Thermal Spectrum Close to Black-Body Shape

☞ **Harvard Classification**

– **OBAFGKM**

☞ $T_{\text{eff}} \sim 2000 \dots 40000\text{K}$

★ Characteristic Lines

☞ **Absorption from Gas above Photosphere**

☞ **Emission from Recombining Gas**

★ HE Phenomena:

☞ **Wind Interactions**

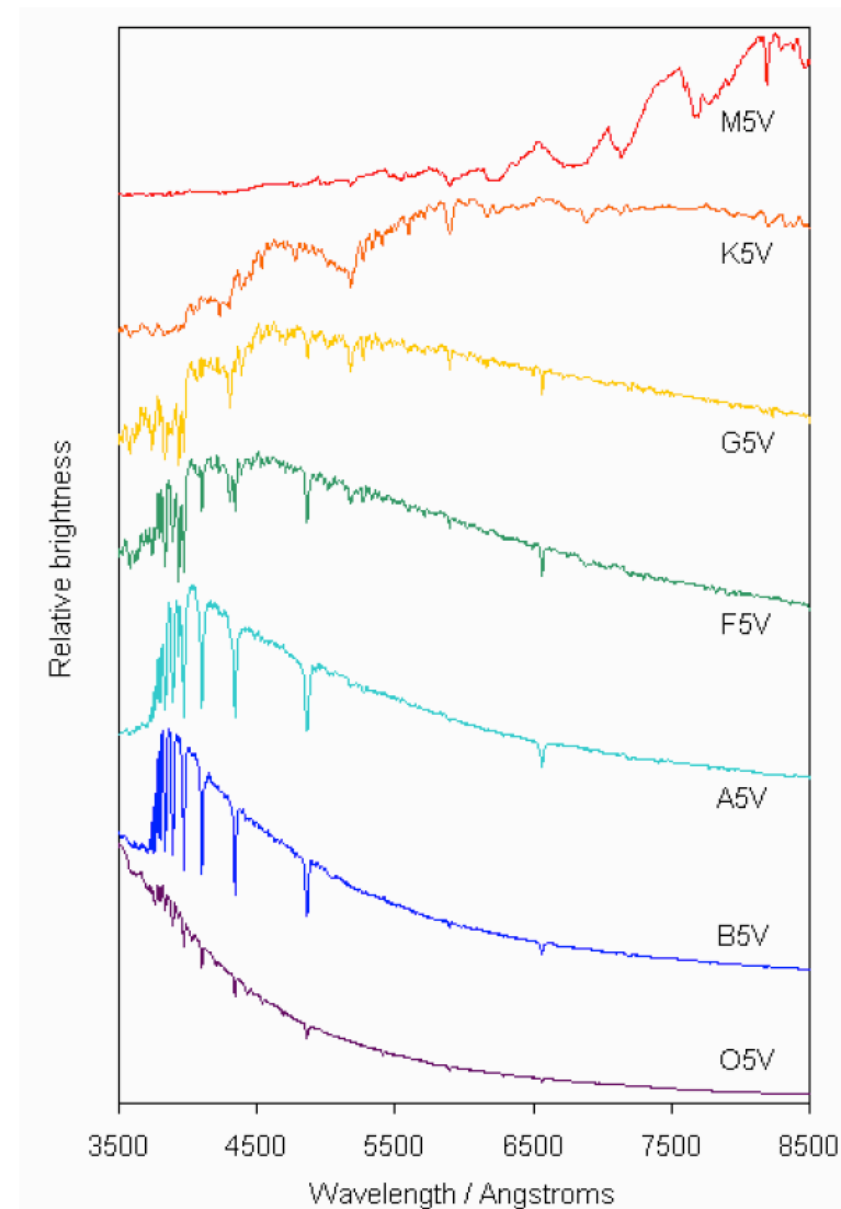
» **Be Systems, O Stars, WR Stars**

☞ **Coronal Flare Emission**

» **T Tau Stars, ...**

☞ **Compact Stars**

» **Accretion → Release of Gravitational Energy**
 » **Nuclear Explosions → Release of Nuclear Energy**
 » **NS Surface; Pulsars**



White Dwarf Spectra



★ Typical Parameters

- ☞ **Mass $\sim 0.5 M_{\odot}$**
- ☞ **Radius $\sim 10000 \text{ km}$**
- ☞ **$T_{\text{eff}} \sim 20000 \text{ K}$**

★ Stabilized by Degenerate e Pressure

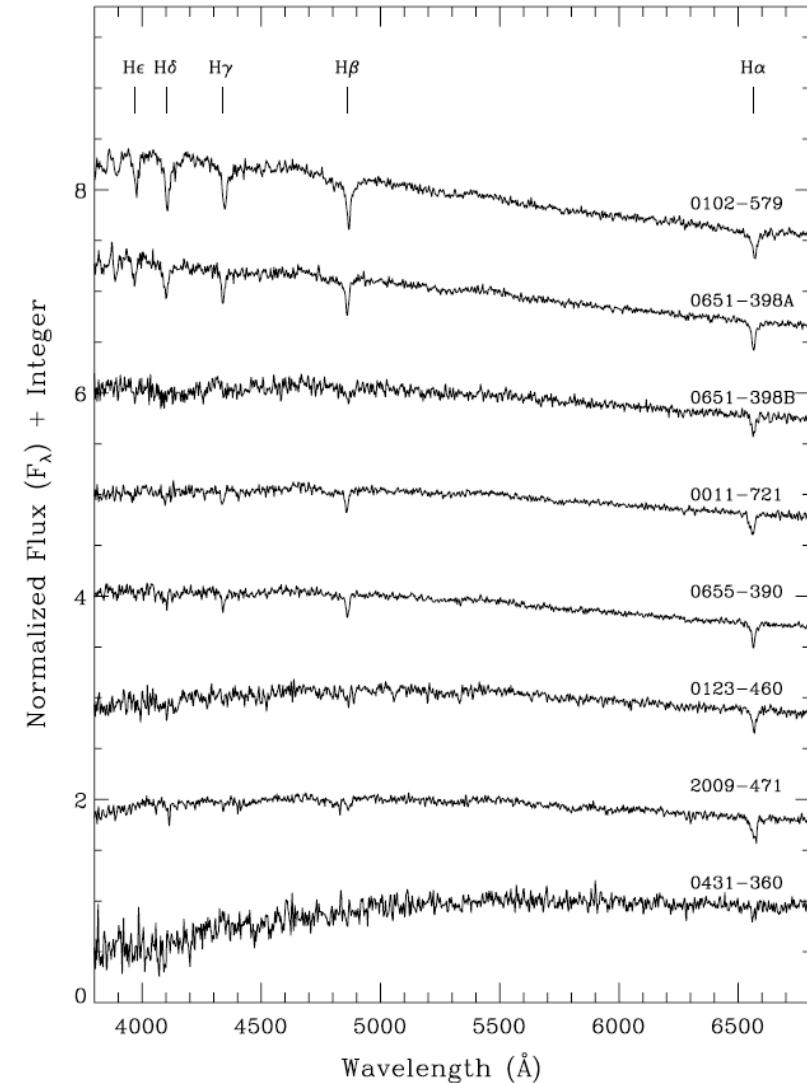
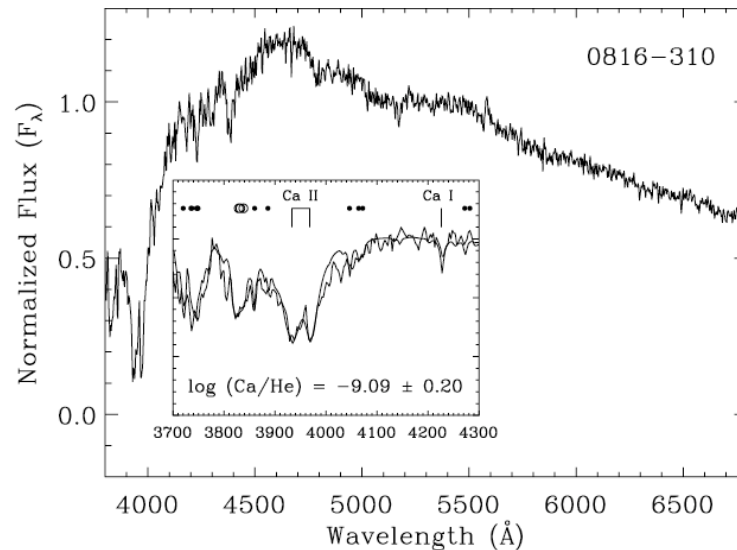


Figure 4. Spectral plots of cool ($T_{\text{eff}} < 10,000 \text{ K}$) DA WDs from the new sample, plotted in descending T_{eff} as derived from the SED fits to the photometry. Spectra have been normalized at 5200 \AA and offset by integer amounts. The asymmetry in the H α feature in the spectrum of WD 2009-471 is the result of a cosmic ray landing just redward of H α that could not be reliably removed.

HE Emission from Compact Stars

★ HE Emission from WDs

☞ Coronal Emission

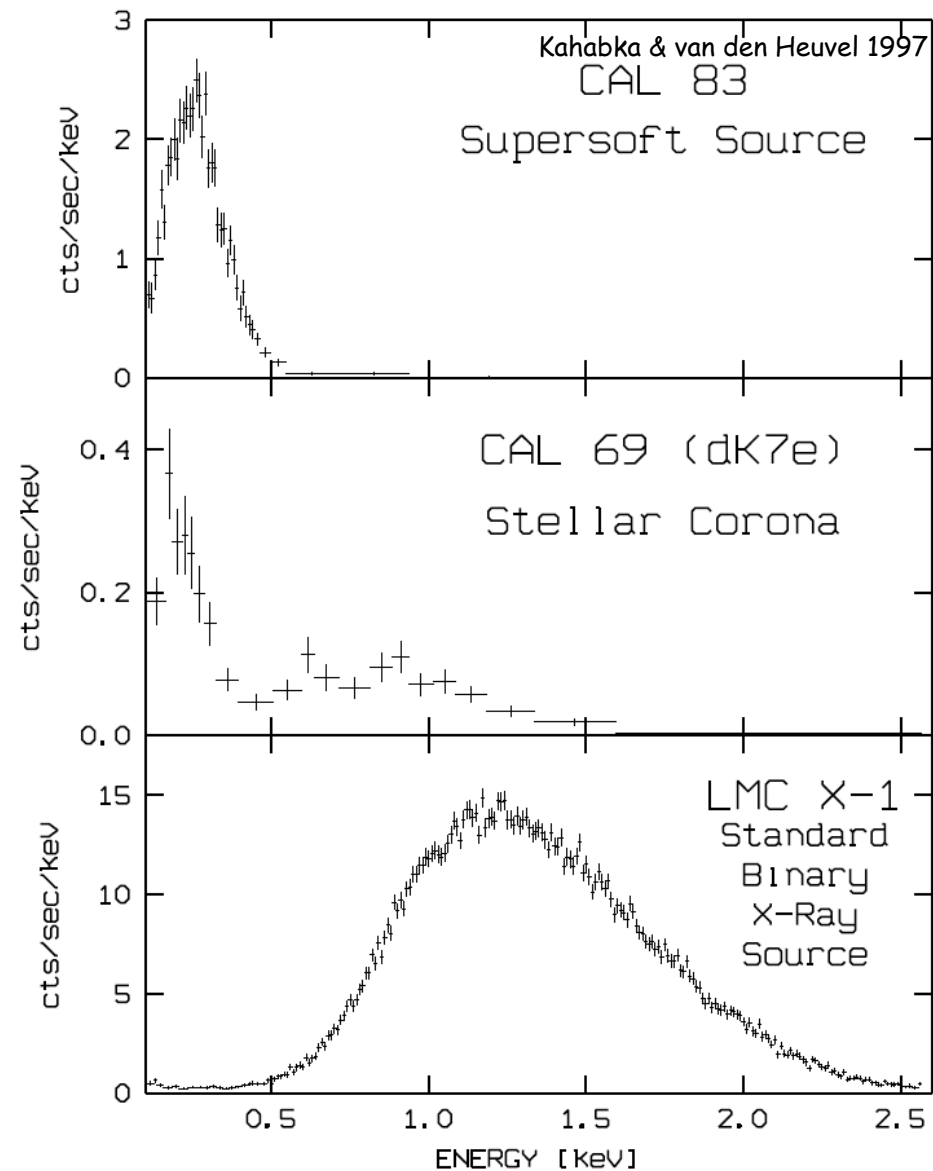
- Hot Plasma
- Bremsstrahlung

☞ Accretion Luminosity

- Binary System
- Substantial Material Transfer

☞ Nuclear Burning

- Binary System
- Low-level Mass Transfer



HE Emission from Compact Stars



★ HE Emission from NS

- ☞ **Stabilized by Nuclear-Matter Density**
– ($10^{13} \text{ g cm}^{-3}$)
- ☞ **Typical Radius 15 km**
- ☞ **Typical Mass $1.4 M_{\odot}$**
- ☞ **Emission from Cooling of NS Interior**

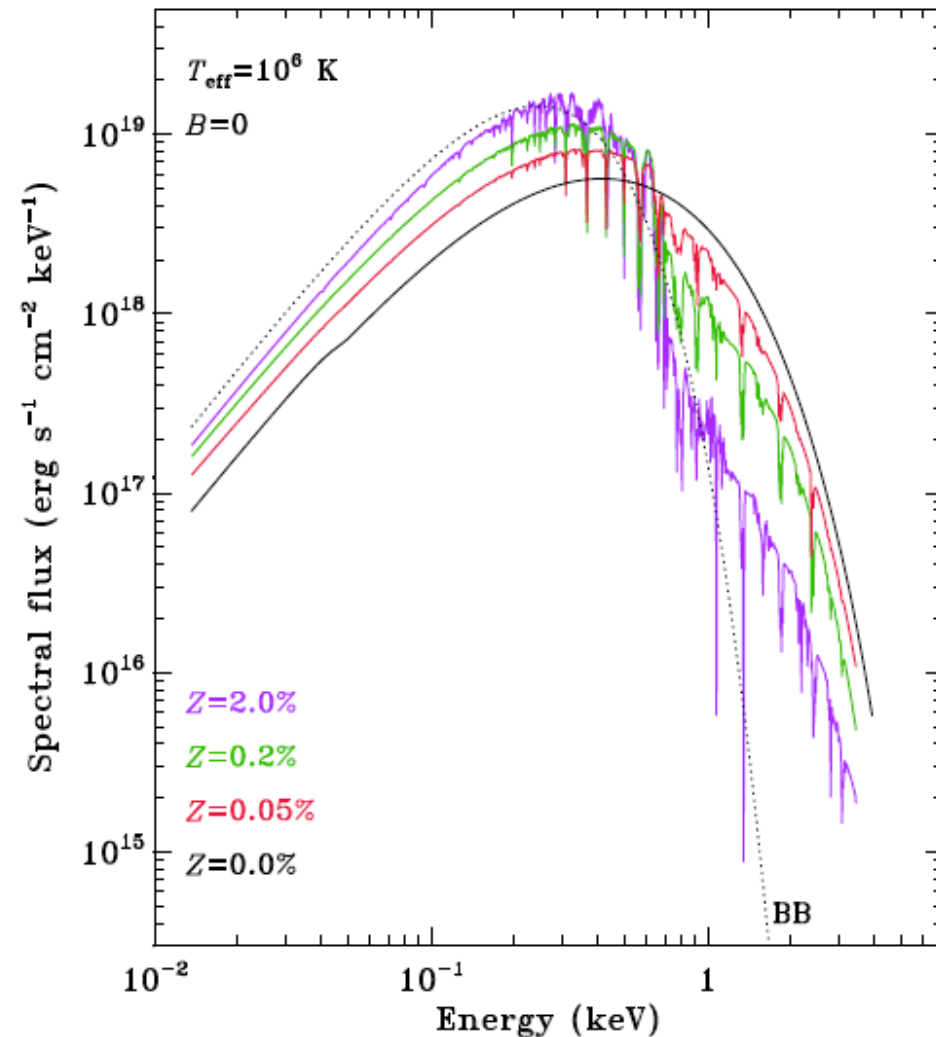
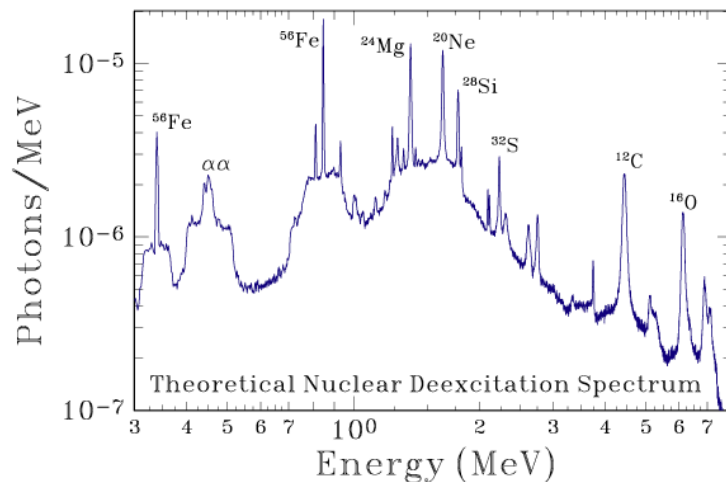
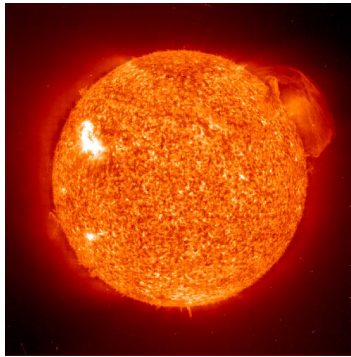
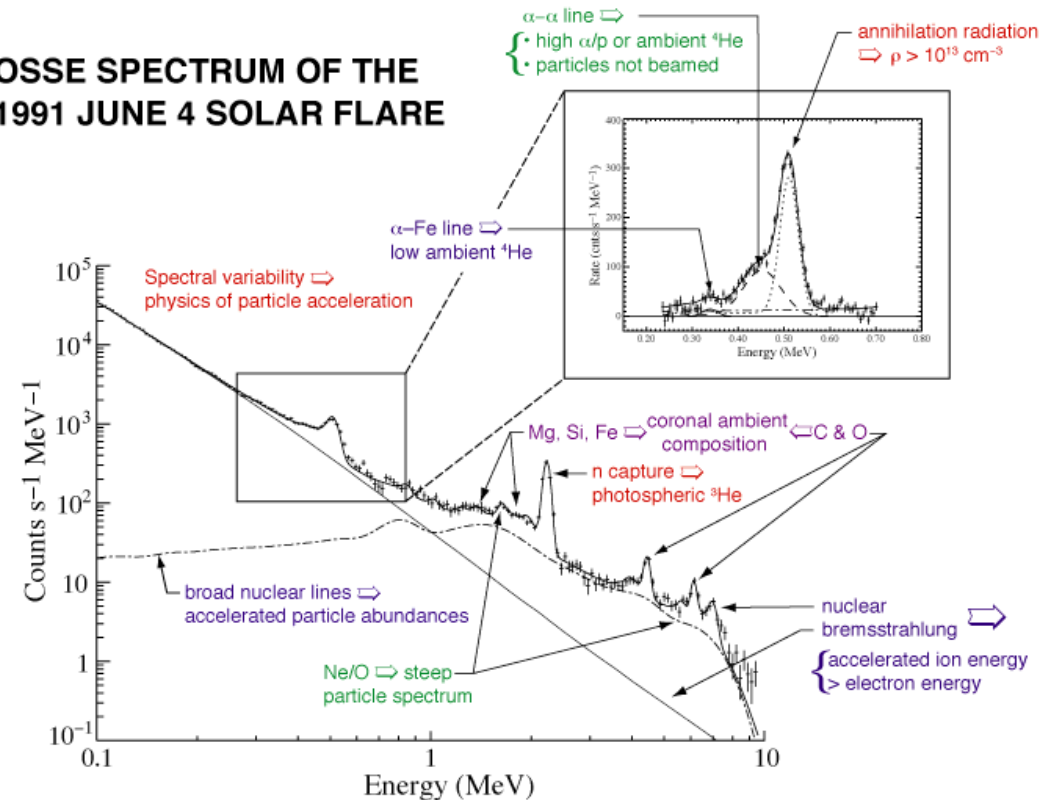


Fig. 8.9. Spectra of emergent radiation in non-magnetic neutron star atmospheres having $T_{\text{eff}} = 10^6$ K for different metallicities Z ($Z = 2.0\%$ corresponds to solar metallicity.) The corresponding blackbody is shown with a dotted line. From Zavlin & Pavlov (2002).

Solar Flares: Laboratories for Particle Acceleration



OSSE SPECTRUM OF THE 1991 JUNE 4 SOLAR FLARE



- Particle Acceleration from Magnetic-Field Reconfigurations
- Interactions of Energetic Particles with Solar Matter

Hot Plasma Emission



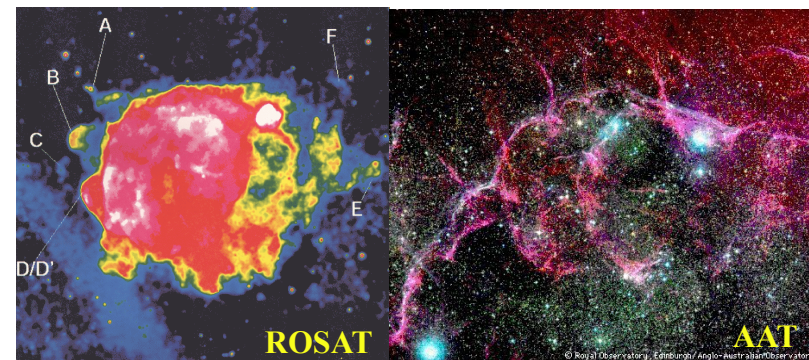
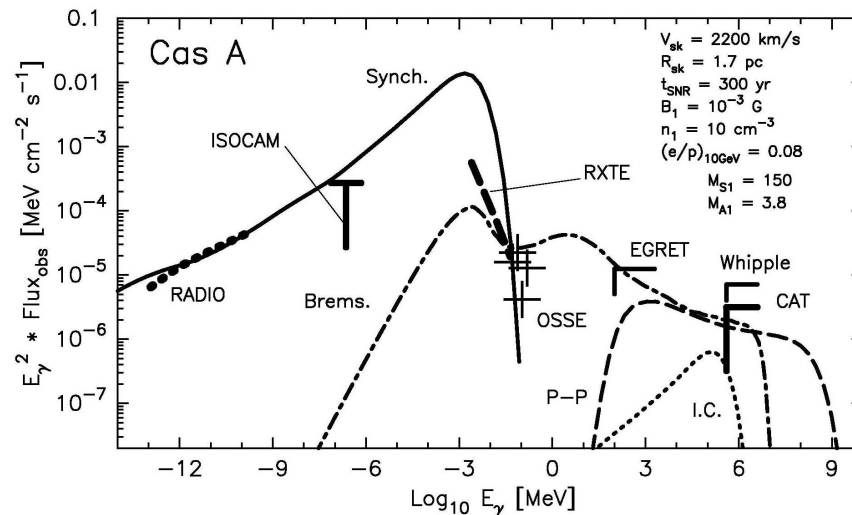
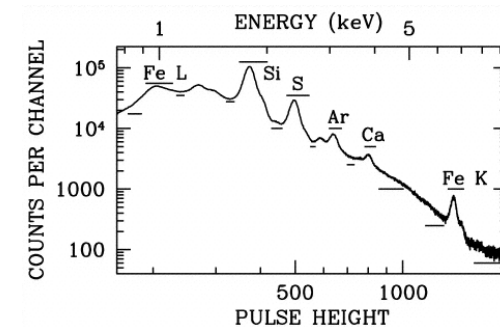
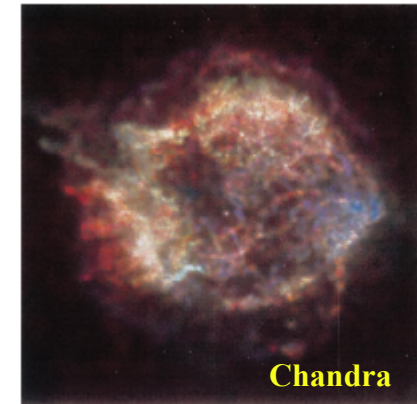
- $T \gg 6000K$

☞ **Matter Ionized: Ions and Electrons**

☞ **Processes:**

- Coulomb Scatterings
- Bremsstrahlung / Free-Free Radiation
- Recombinations / Ionizations
- Comptonization / Compton Scattering

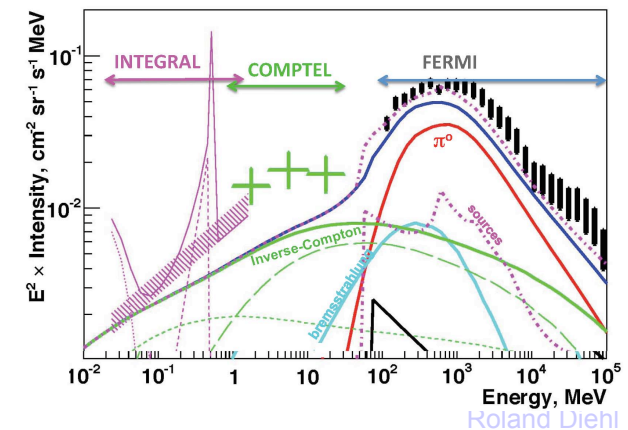
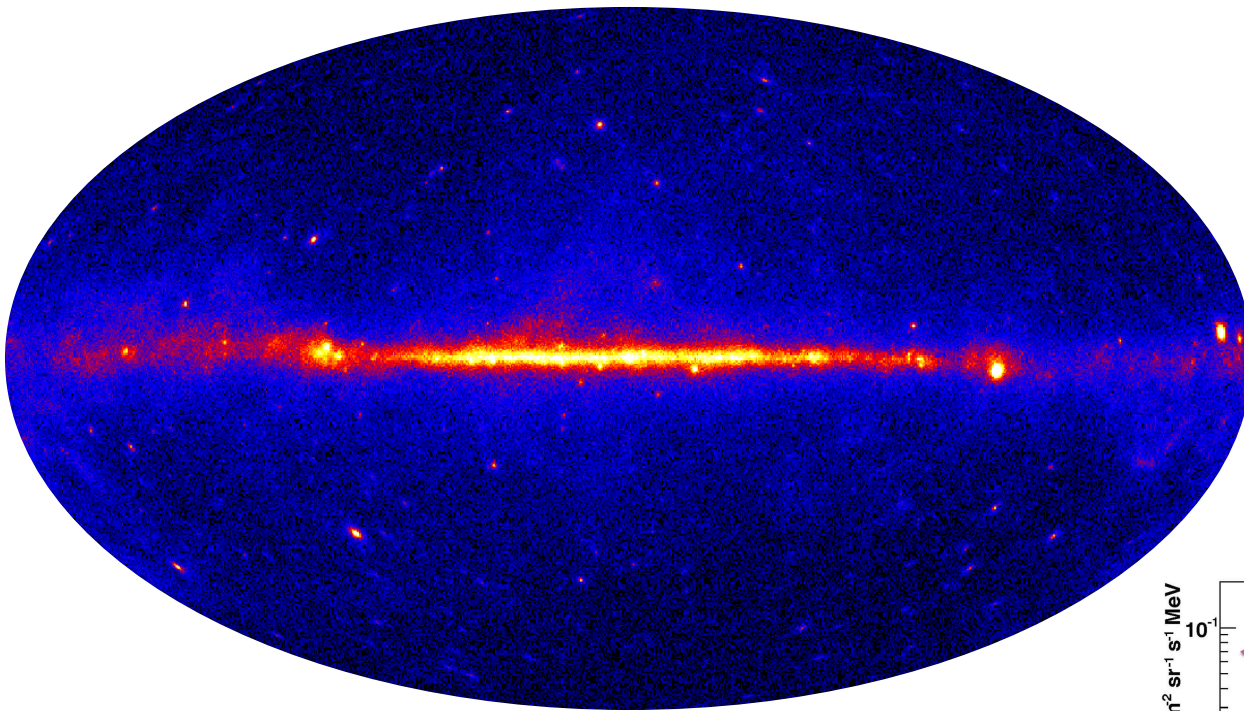
☞ **Thermal and Non-Thermal Particle Populations**
 (-> Different Radiation Components)



HE Gamma-Ray Emission from the Galaxy



★ The GeV Sky as Seen by FERMI/LAT (2009; 1 yr)

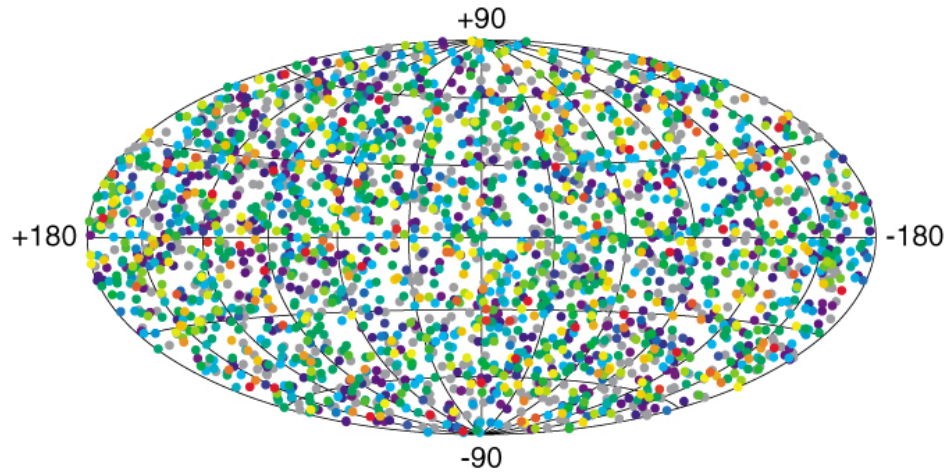


Gamma-Ray Bursts: Forming First Black Holes?

prompt

afterglow

2704 BATSE Gamma-Ray Bursts



BATSE—GRO 3 Types of Gamma-Ray Bursts 50-300 keV

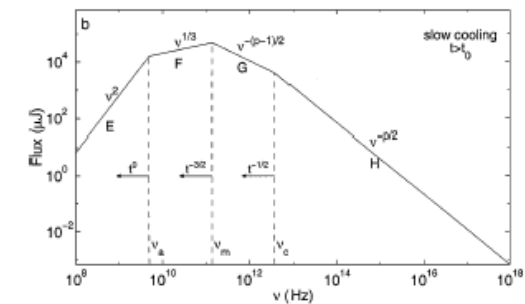
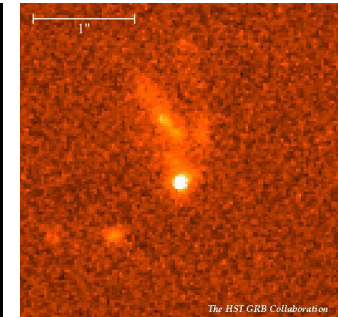
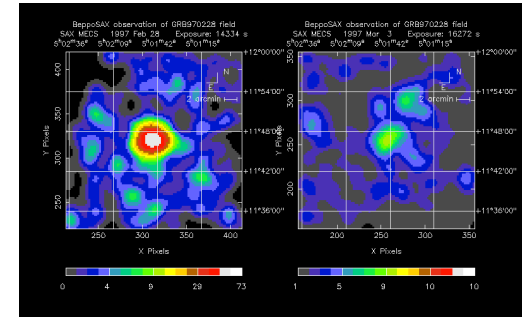
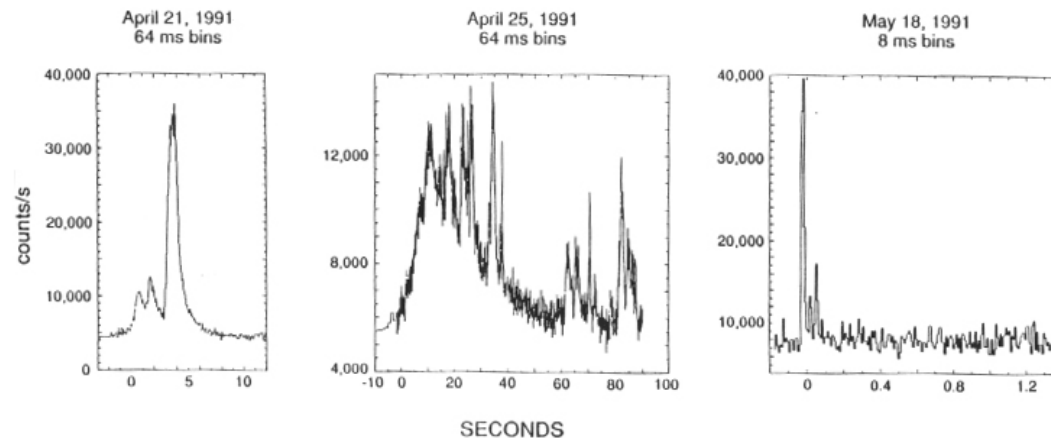
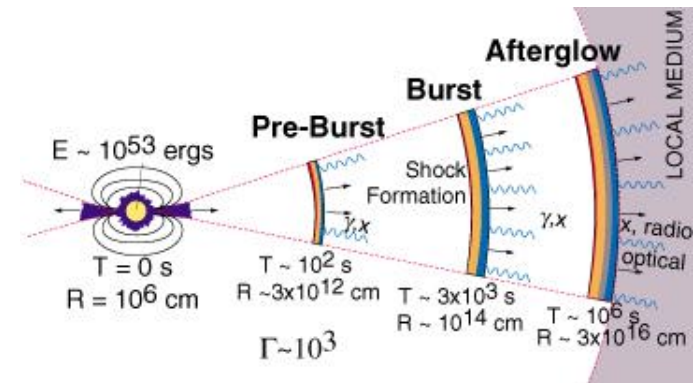
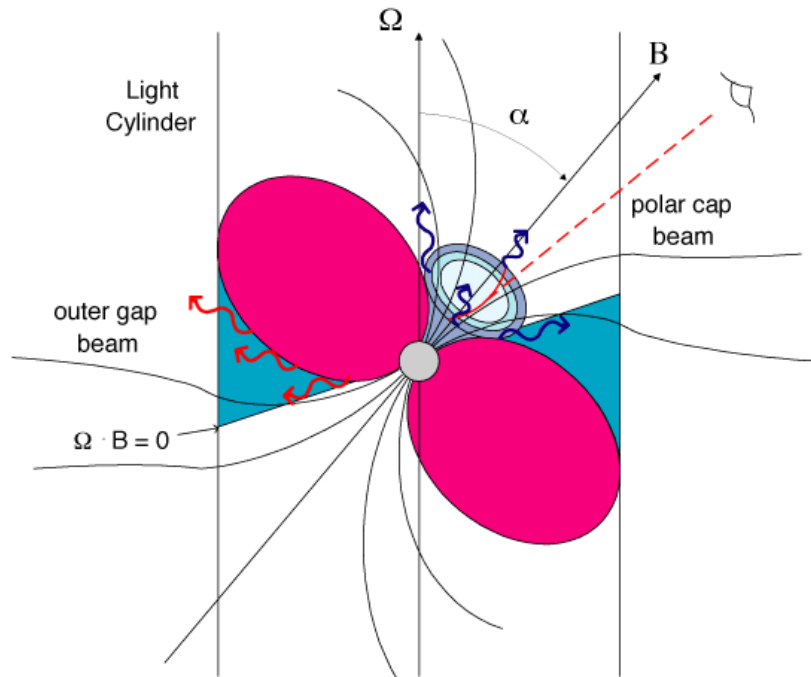


Figure 3 The piecewise power-law schematic shape of blast wave synchrotron spectra for later afterglow evolution (Sari et al 1998). The characteristic break frequencies and their time evolution are indicated, as is the spectral slope in each regime. This can be directly compared with the observed spectrum of GRB 970508 (Figure 12).



High-Energy Interactions of Cosmic Matter



- Relativistic Particles Interact with:

- ★ **Electromagnetic Fields**

- ☞ Curvature Radiation
 - ☞ Synchrotron Radiation
 - ☞ Bremsstrahlung
 - ☞ Pair Creation

- ★ **Particles, Atoms**

- ☞ Nuclear Excitation
 - ☞ Spallation

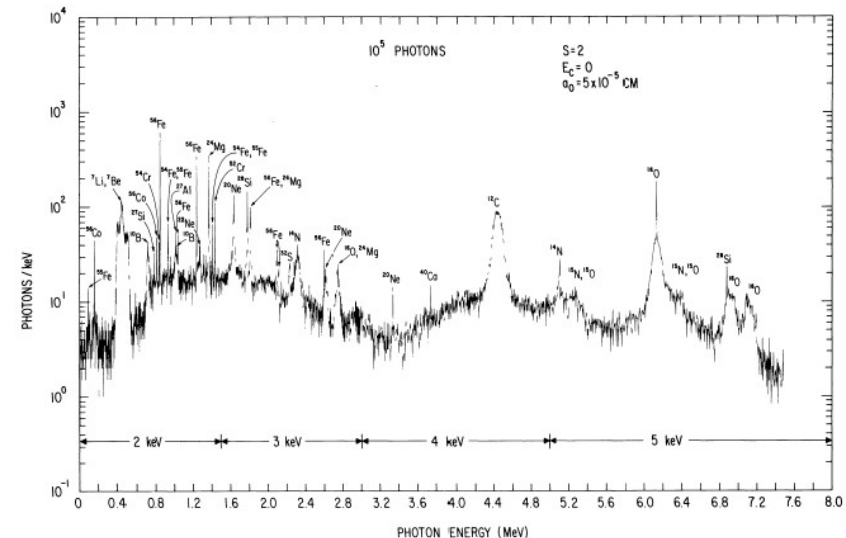
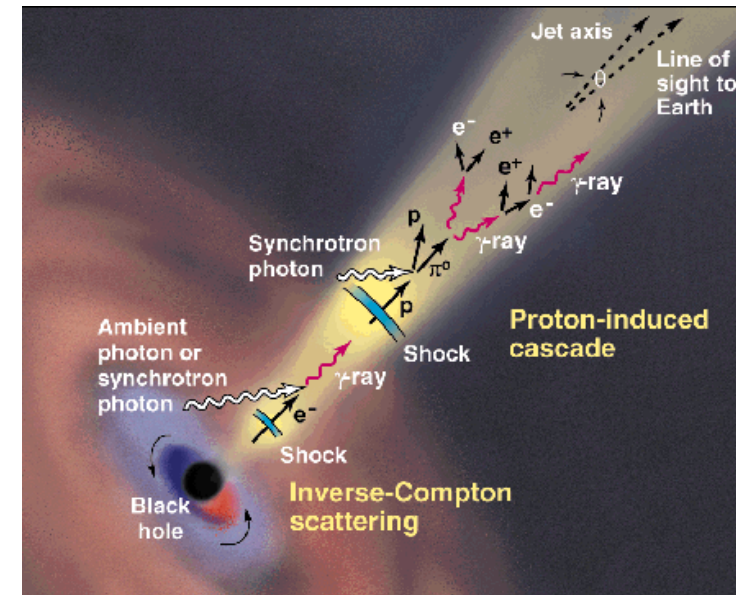


FIG. 18.—Monte Carlo simulated γ -ray spectrum for energetic particles and ambient medium having solar compositions; S and E_c are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

Cosmic Photons

- Sources

- ★ Thermal Emission ($\sim 10^{5-9}$ K Blackbody; Fireball)

- ★ Continuum Radiation from Accelerated Charged Particles

- ☞ Bremsstrahlung (e⁻ & nuclei)

- ☞ Synchrotron Radiation (e⁻ and magnetic field)

- ☞ Inverse Compton Radiation (e⁻ and low-energy photons)

- ★ Line Radiation from QM System Transitions

- ☞ Characteristic X-rays (atomic shell)

- ☞ Cyclotron Radiation (magnetic field)

- ☞ Annihilation of Positrons (e.m. field)

- ☞ Characteristic g-rays (atomic nucleus)

- ☞ Decay of Pions (nucleonic interactions)

- Attenuation Processes

- ★ Inelastic Scattering Processes

- ☞ Compton Scattering

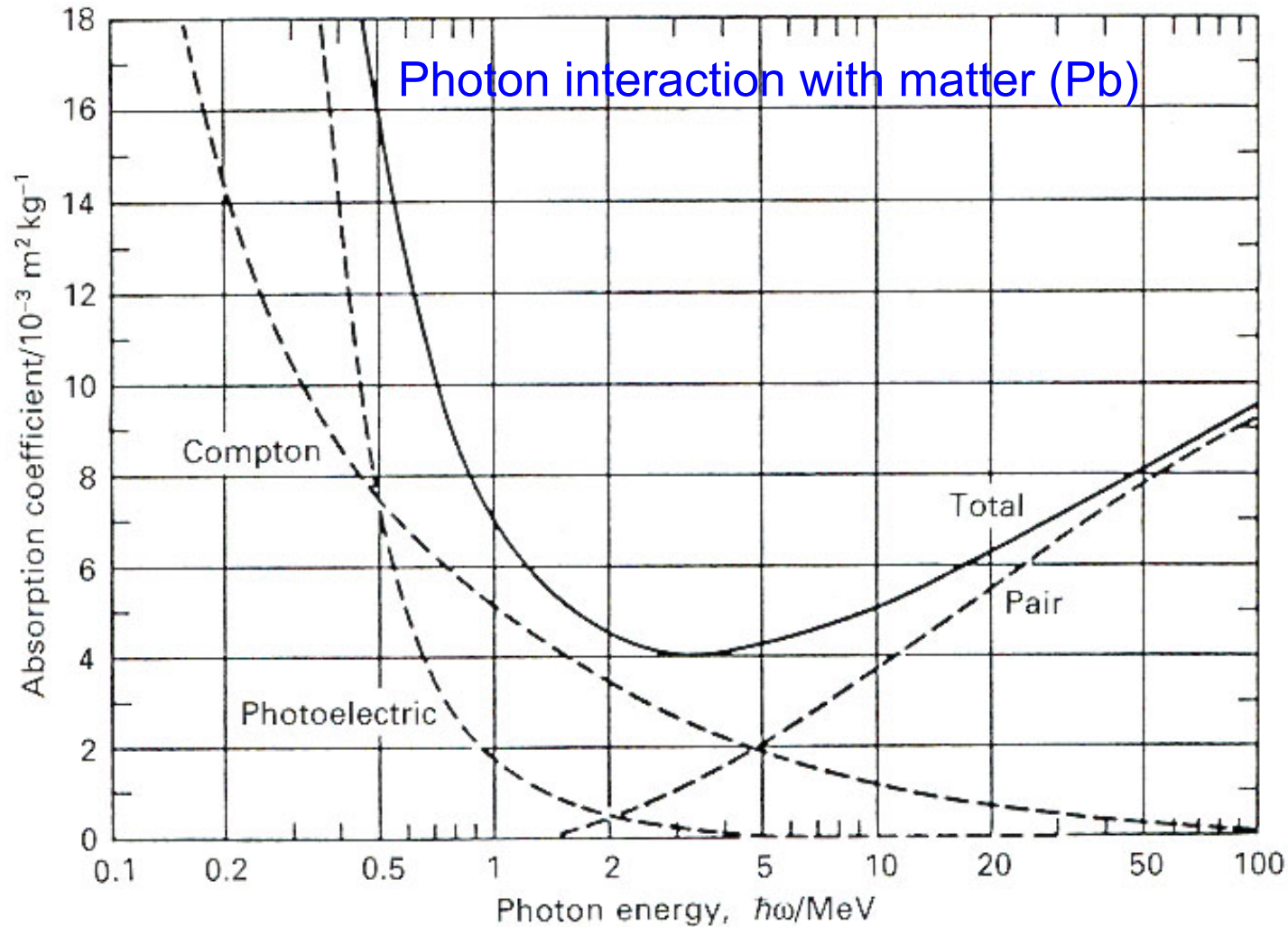
- ☞ Photo-ionization

- ★ Pair Production

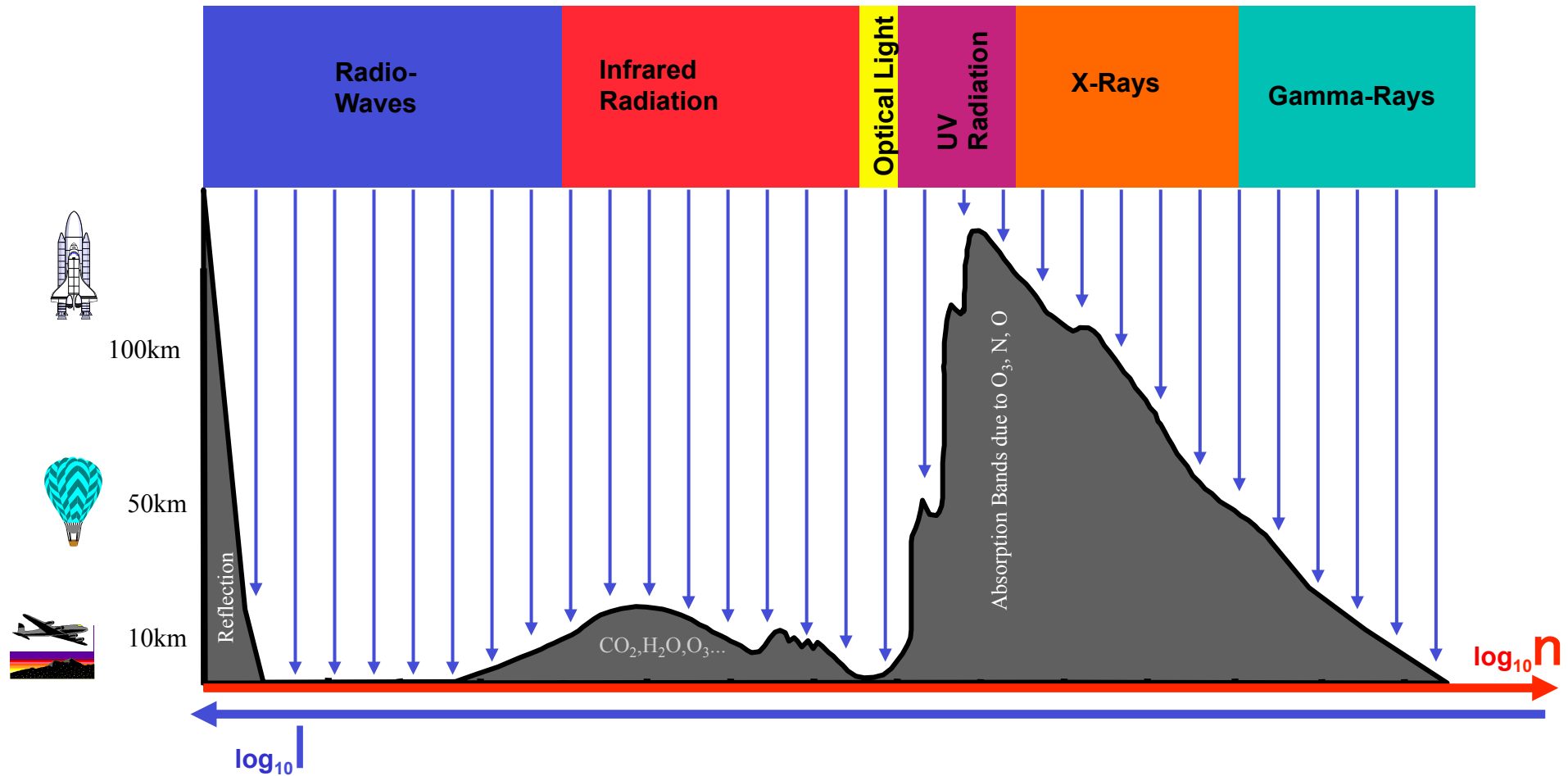
Radiation Processes

- Thermal Radiation
- Radiation from (Accelerated) Charges
 - ★ Bremsstrahlung
 - ★ Synchrotron Radiation
 - ★ Curvature Radiation
- Electron - Photon Scattering
 - ★ Thompson Scattering
 - ★ Compton Scattering
- Transitions in QM Systems
 - ★ Atomic Transitions
 - ★ Nuclear Transitions
- Positron Annihilation
- Pion Decay
- ...

Interaction of HE photons with matter



Observational Windows



- Need a Combination of Ground-Based and Satellite Observations for Observations across Full Range
- Which Processes in Which Spectral Window?

Astronomical Instruments



- **Optical Telescopes**
- **Radio Telescopes**
- **Infrared Detector Systems**
- **UV Telescopes**
- **X-Ray Telescopes**
- **Gamma-Ray Detectors**
- **Cosmic-Ray Detectors**
- **Meteorites**
- **Neutrino Telescopes**
- **Gravity Wave Detectors**

High-Energy Astronomy

- **Measurement of Electromagnetic Radiation**

- ★ **Issues:**

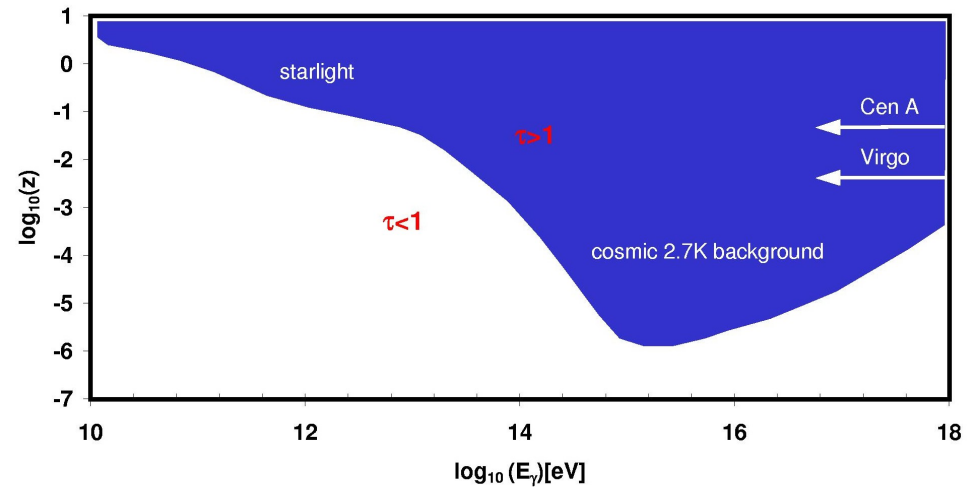
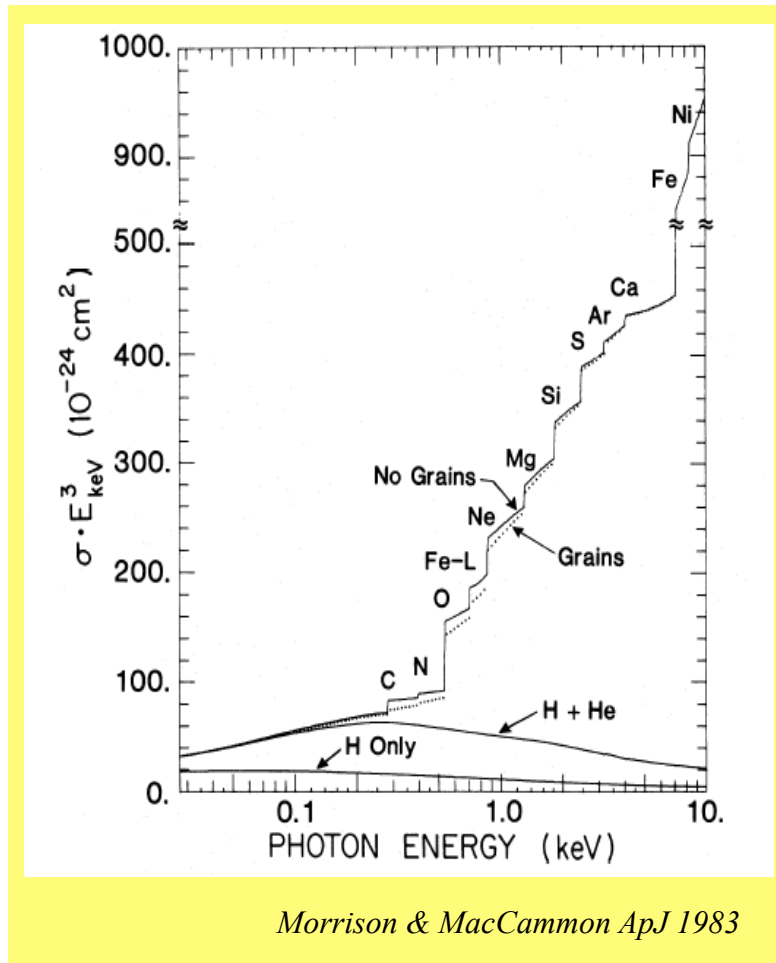
- ☞ **Energy Output of Source Objects (per n Band)**
 - ☞ **Characteristic Source Processes**
 - ☞ **Physical Conditions in the Object**
 - ☞ **Superposition of Radiation from Different Objects**
 - ☞ **Absorption, Distortion, and Occultation of Radiation**

- **Measurement of Cosmic-Ray Particles**

- ★ **Issues:**

- ☞ **Energy Output of Source Objects (per Band; 'SED')**
 - ☞ **Characteristic Source Processes**
 - ☞ **Physical Conditions in the Object**
 - ☞ **Superposition of Sources**
 - ☞ **Propagation of Cosmic Rays**

Transparency of the Universe at High Energy



Interaction of Photons

★ Absorption (Dust, Gas)

☞ Structure from

- Dust Particles, Molecules
- Atomic-Shell Electrons

★ Scattering

☞ Elastic

☞ Inelastic

- Compton Scattering
- Pair Creation

$$\tau_x = 2 \cdot 10^{-26} \left(\frac{h\nu}{1\text{keV}} \right)^{-8/3} \int N_H dl$$

High-Energy Astrophysics

End of Part 1

Key Messages:

- ★ **“High energy” is a relative definition**
 - ☞ **Astrophysical processes and their energy scale**
 - ☞ **Astronomical observations and their techniques & constraints**
- ★ **Main objects of interest are**
 - ☞ **Nuclear processes, i.e. enrichment of cosmos with variety of nuclei**
 - ☞ **Relativistic particle acceleration, emission related to relativistic particles**
- ★ **This involves astrophysics of**
 - ☞ **Stellar structure and supernova explosions**
 - ☞ **Compact stars, their formation as well as processes on their surfaces**
 - ☞ **Interstellar medium: hot phases**
 - ☞ **Hot plasma in jets from extreme environments (AGN, GRB)**
 - ☞ **Cosmic ray interactions**
- ★ **Instrumentation differs from conventional “telescopes”**

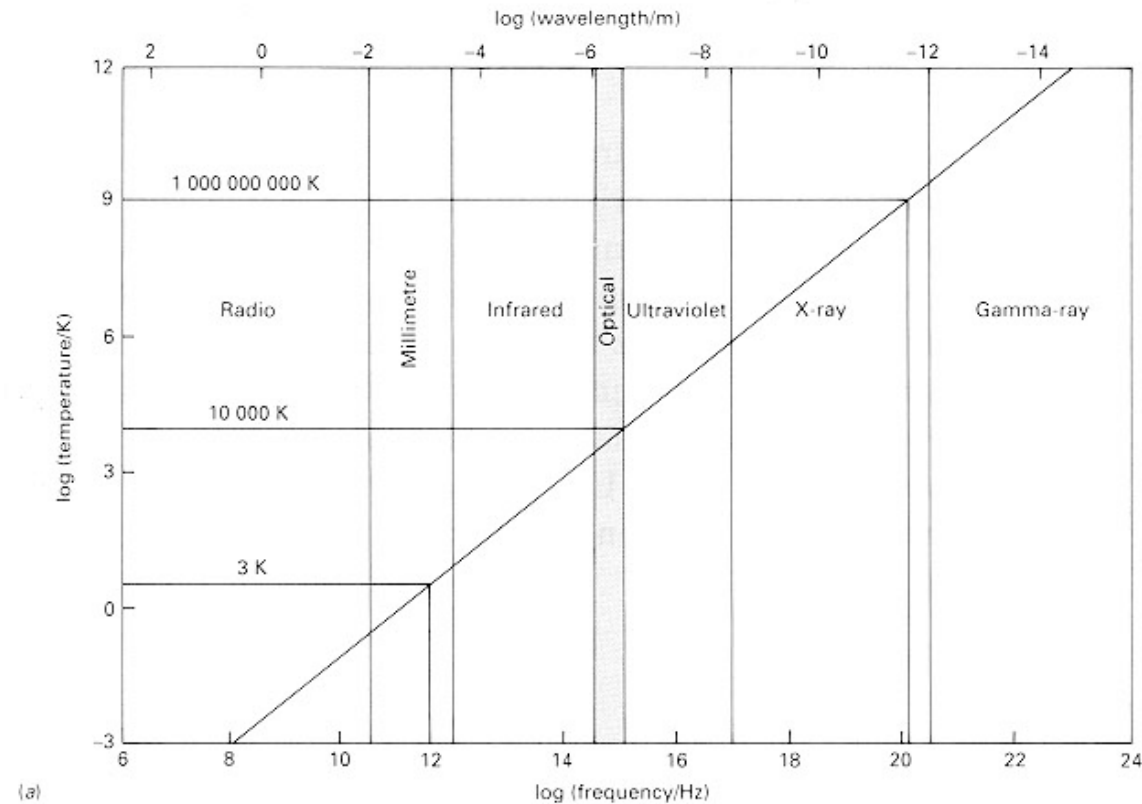
High-Energy Astrophysics

Part 2

Radiation Processes

★ Thermal Emission

Thermal/non-Thermal Cosmic Radiation



- **Plausible Cosmic Sources of Thermal (Blackbody) Radiation**
 - ☞ Optical: Stars $T \sim 10.000\text{K}$
 - ☞ Infrared: Dust $T \sim 30\text{K}$
 - ☞ Radio: Gas $T \sim 10\text{K}$
 - ☞ X-Rays: Hot Plasma $T \sim 1.000.000\text{K}$
- **Astronomical Windows for Non-Thermal Radiation**
 - ☞ Radio
 - ☞ X and Gamma-Rays

About Multi-Particle Systems

★ Thermalized Systems

- 👉 Particle Interactions Ensure Equal Populations of States
- 👉 Boltzmann Equation \leftrightarrow Thermal State Occupancies

★ Degenerate Matter

- 👉 Fermions Cannot Occupy Identical States (Pauli)
- 👉 Phase Space Dictates State Occupancy \rightarrow Fermi Distribution

Dense
Matter

Compact
Stars

★ Collisionless Systems

- 👉 Particles are Subject to External and Self-Generated Fields
- 👉 Phase Space Occupancy is Significant for Particle Dynamics

Diluted
Matter

IGM, ISM,
Cosmic
Rays

Blackbody Radiation



1. Planck functions (Brightness of a blackbody)

$$B_\nu(T) = \frac{2 h \nu^3}{c^2} \frac{1}{(\exp \frac{h\nu}{kT} - 1)} \quad \text{erg cm}^{-2} \text{sec}^{-1} \text{Hz}^{-1} \text{ster}^{-1}$$

$$B_\lambda(T) = \frac{2 hc^2}{\lambda^5} \frac{1}{(\exp \frac{hc}{\lambda kT} - 1)} \quad \text{erg cm}^{-2} \text{sec}^{-1} \text{cm}^{-1} \text{ster}^{-1}$$

$$B_{\tilde{\nu}}(T) = \frac{2 hc^2 \tilde{\nu}^3}{(\exp \frac{hc\tilde{\nu}}{kT} - 1)} \quad \text{erg cm}^{-2} \text{sec}^{-1} (\text{cm}^{-1})^{-1} \text{ster}^{-1}$$

$$B_\nu(T) d\nu = B_\lambda(T) d\lambda = B_{\tilde{\nu}}(T) d\tilde{\nu}$$

Rayleigh-Jean's law

$$h\nu / kT \ll 1$$

$$B_\nu(T) = 2 \left(\frac{\nu}{c} \right)^2 kT$$

Wien's law

$$h\nu / kT \gg 1$$

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \exp \frac{-h\nu}{kT}$$

2. Stefan-Boltzmann law

$$\text{total emittance} = \pi \int_0^\infty B_\nu(T) d\nu = \sigma T^4 \quad \text{ergs cm}^{-2} \text{sec}^{-1}$$

$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{deg}^{-4} \text{sec}^{-1}$$

3. Wien displacement law

Maximizing B_ν :

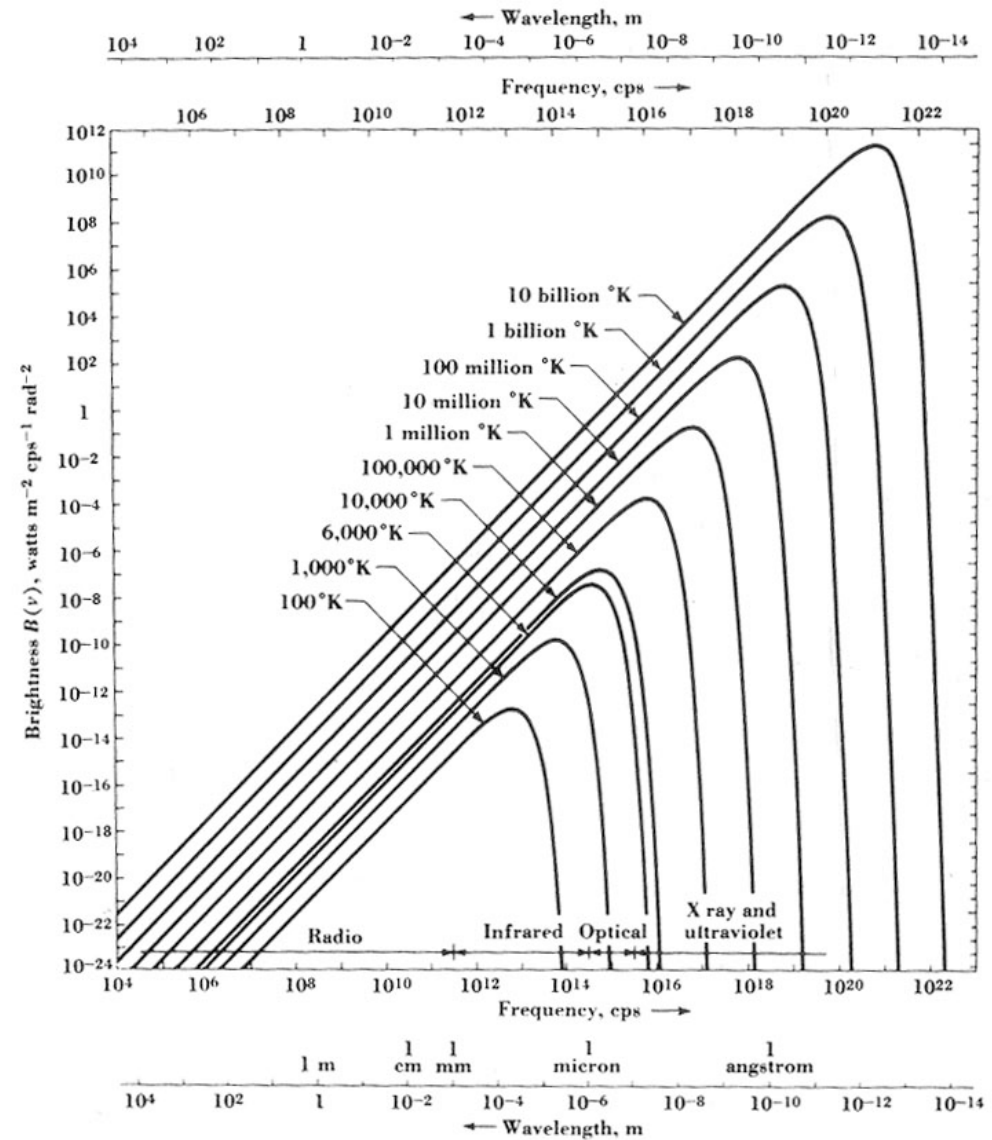
$$\nu_m = 5.9 \times 10^{10} \text{ T Hz}$$

$$\lambda_m = 0.51 \text{ T}^{-1} \text{ cm}$$

Maximizing B_λ :

$$\nu_m = 10.3 \times 10^{10} \text{ T Hz}$$

$$\lambda_m = 0.29 \text{ T}^{-1} \text{ cm}$$



Blackbody Radiation at High Energies

★ Temperature Range $10^6 \dots 10^{10}\text{K}$

★ Issues for Thermal Sources in this Range:

☞ Ionization of Atoms at $10^4\text{K}+$

→ Hot Plasma

☞ Nuclear Fusion Reactions at $10^7\text{K}+$ → Stellar Interiors (occulted)

☞ Pair Production Threshold $\sim 1 \text{ MeV}(10^9\text{K})$

→ Optically-thick Source

☞ Radiation Pressure: $P_{\text{rad}} = \frac{1}{3} a T^4$ $a \approx 7.6 \cdot 10^{-15} \left[\frac{\text{erg}}{\text{cm}^3 \text{K}^{-4}} \right]$ → Unstable Source

★ Most-Plausible Source of Thermal HE Emission:

☞ Accretion onto Compact Stars (no occulting envelope)

Maximum Luminosity of Stellar Source

★ Accretion Luminosity

$$L = \varepsilon \cdot \frac{GM_C}{R_C} \cdot \frac{dM}{dt}$$

☞ Neutron Star Accretion:

$$L = \varepsilon \cdot 2.95 L_{sun} \left(\frac{R}{10^6 \text{ cm}} \right)^{-1} \left(\frac{M_C}{1.4 M_{sun}} \right) \left(\frac{1}{10^{-12} M_{sun} \text{ y}^{-1}} \right) \cdot \frac{dM}{dt}$$

☞ Stability of Accretion Flow:

– Radiation Pressure

$$F_{rad} \approx \frac{L \cdot \sigma_{Th}}{4\pi cr^2}$$

– Gravity

$$F_{grav} \approx \frac{GM_C m_{proton}}{r^2}$$

– Extrema:

Luminosity $L_E = \frac{4\pi G m_{proton} c}{\sigma_{Th}} \approx 1.3 \cdot 10^{46} \left(\frac{M_C}{10^8 M_{sun}} \right) \cdot \left[\frac{\text{erg}}{\text{s}} \right] = 10^{4.5} \left(\frac{M_C}{M_{sun}} \right) \cdot L_{sun}$ ("Eddington Luminosity")

Accretion Rate $\dot{M}_E \approx 1.5 \cdot 10^{-8} \left(\frac{R}{10^6 \text{ cm}} \right) \cdot \left[\frac{M_{sun}}{\text{y}} \right]$

Pair Production Limit

★ **Process:** $\gamma + \gamma \rightarrow e^+ + e^-$

★ **Threshold energy: 1.022 MeV** $E_{\text{th}} = 2 m_e c^2$

★ **Photons from HE process (γ) interact with photons from**

☞ **Thermal emission at lower temperatures (X)**

☞ **Starlight**

☞ **Dust**

☞ **Cosmic background radiation**

★ **Typical high-energy continuum-photon sources:**

☞ **Pulsars**

☞ **Gamma-Ray Bursts**

☞ **Jets in Active Galaxies**

★ **All of these (probably) also eject plasma at relativistic energies**

☞ **Effective pair production threshold increased in relativistic flows:**

– **Co-moving Photons and Plasma**

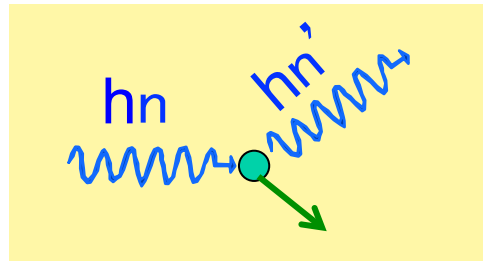
– **Beamed Emission / Jets \rightarrow Sufficiently-Large Collision Angles are Unlikely**

$$\gamma \gtrsim 10^2 (\epsilon_\gamma / 10 \text{ GeV})^{1/2} (\epsilon_t / \text{MeV})^{1/2}$$

Radiation Interactions with Charged Particles

Compton Scattering

- ☆ E Field of Photon Accelerates Charge → Photon Emission
- ☆ Momentum and Energy Transfer to e-



$$\frac{1}{\nu'} - \frac{1}{\nu} = \frac{h}{m_e c^2} (1 - \cos \theta)$$

$$\frac{h}{m_e c} = \lambda_C = 2.426 \times 10^{-10} \text{ cm}$$

☆ Compton Cross Section:

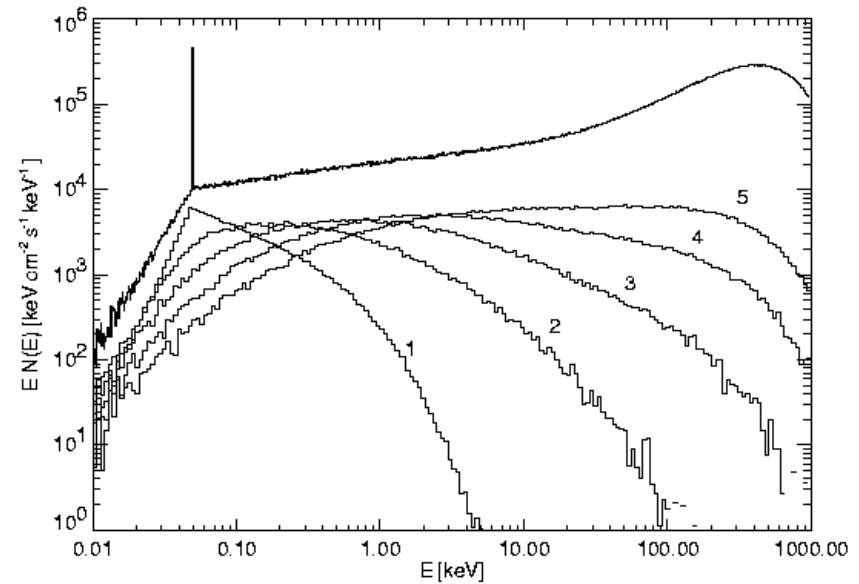
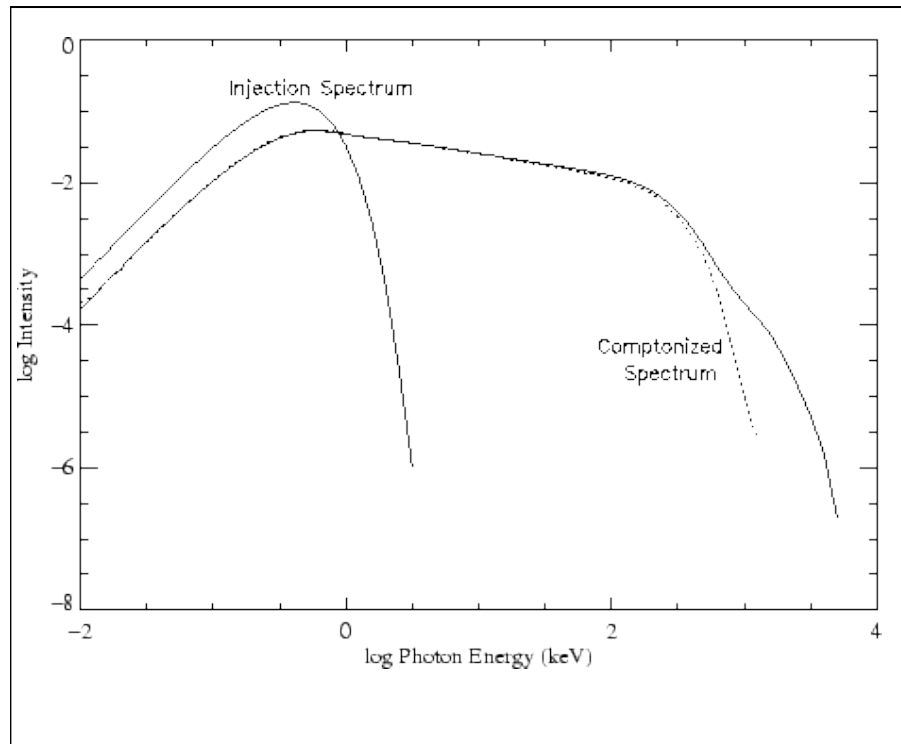
👉 **Arthur Holly Compton (1892-1962), 1927 Nobel Prize (particle concept of em)**

👉 **Klein Nishina Cross Section, from Q.M. Corrections**

$$\sigma_C = \sigma_{KN} = \frac{3}{8} \sigma_T \frac{1}{\epsilon} \left\{ \left[1 - \frac{2(\epsilon + 1)}{\epsilon^2} \right] \ln(2\epsilon + 1) + \frac{1}{2} + \frac{4}{\epsilon} - \frac{1}{2(2\epsilon + 1)^2} \right\}$$

$$\epsilon = \frac{\hbar \omega}{m c^2}$$

"Comptonization"



Sphere with $\tau = 5$ and $kT_e = 0.4 m_e c^2$ (~ 200 keV), seed photons come from center of sphere.

★ Scattering → energy exchange between e^- and photons (intermediate t)

- ☞ Need rarefied gas (so no additional photons are produced)
- ☞ Hot plasma (so energy gain of photons is significant)

- ☞ For n scatterings, the energy gain is

$$\frac{\varepsilon'}{\varepsilon} = \left(1 + \frac{4kT_e}{m_e c^2}\right)^n \approx e^{\frac{4kT_e}{m_e c^2} n}$$

- ☞ Limiting case: optically-thick plasma,

$$\langle hn \rangle \sim 3kT_e$$

$$\frac{\Delta \varepsilon}{\varepsilon} = -\frac{h\nu}{m_e c^2} + \frac{4kT_e}{m_e c^2}$$

Inverse Compton Scattering

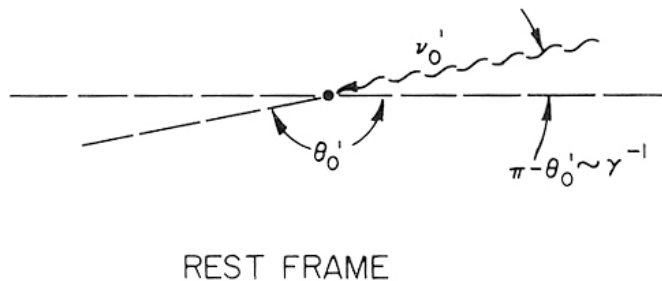
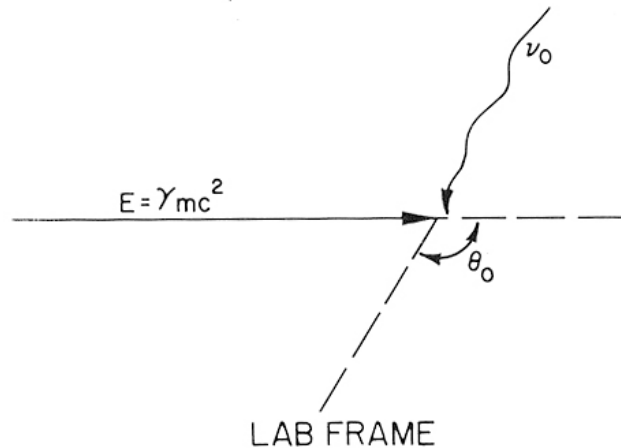


Fig. 3.10. Compton collision between a relativistic electron and low frequency photon as viewed in both the laboratory and the rest frame of the electron.

★ Energy Gain of Photon in a Collision

☞ $E_g = \Gamma^2 h\nu$ for lower energies

☞ $E_g = \Gamma^2 mc^2$ for high (relativistic) energies

Total Power

(= Energy Loss of e^-)

☞
$$-\frac{dE}{dx} = \int \sigma_c(E_\gamma, h\nu) N(h\nu) E_\gamma dE_\gamma d(h\nu)$$

☞ **low-energy situation:**
Thompson scattering

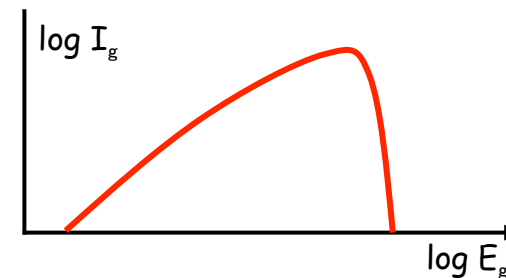
$$\sigma_c = \sigma_{Th}$$

☞ **High energy ($\Gamma h\nu \gg mc^2$):**
Klein-Nishina, $\sim 1/h\nu$

$$\sigma_c \approx \frac{3}{8} \sigma_{Th} \left(\frac{mc^2}{\Gamma h\nu} \right) \left[\ln \left(\frac{2\Gamma h\nu}{mc^2} \right) + \frac{1}{2} \right]$$

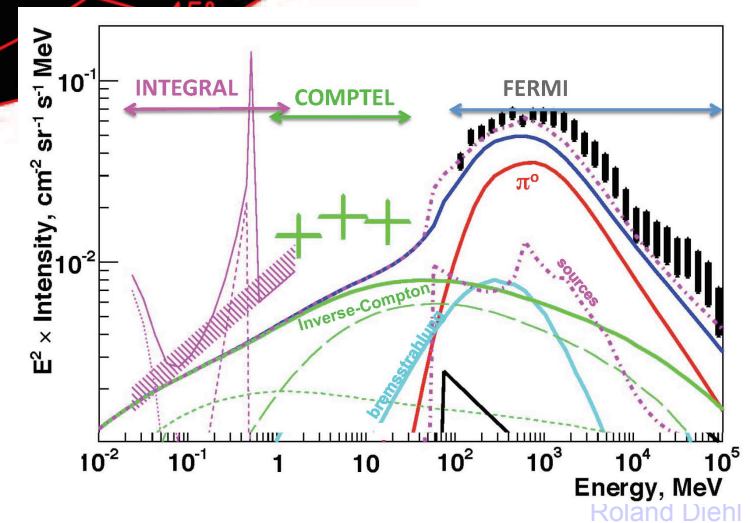
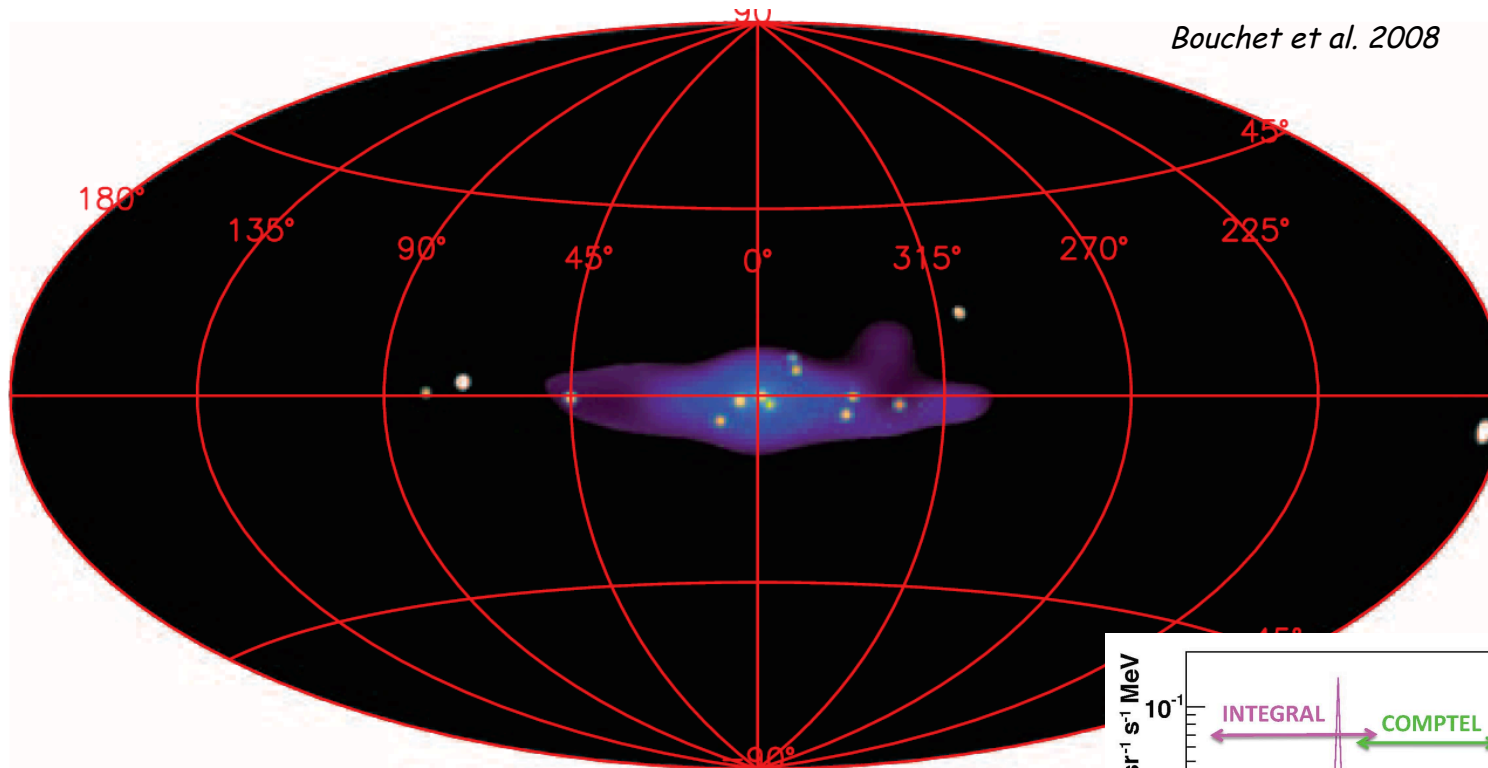
☞ **Energy spectrum $\sim h\nu N(h\nu)$**

☞ **Max Energy $\sim 4 \Gamma^2 E_e$**



The Diffuse Galactic Emission at ~MeV

☆ The Galactic Ridge at 200-600 keV with SPI/INTEGRAL



Example: Cosmic-Ray Accelerator Diagnostics: Leptonic or Hadronic?

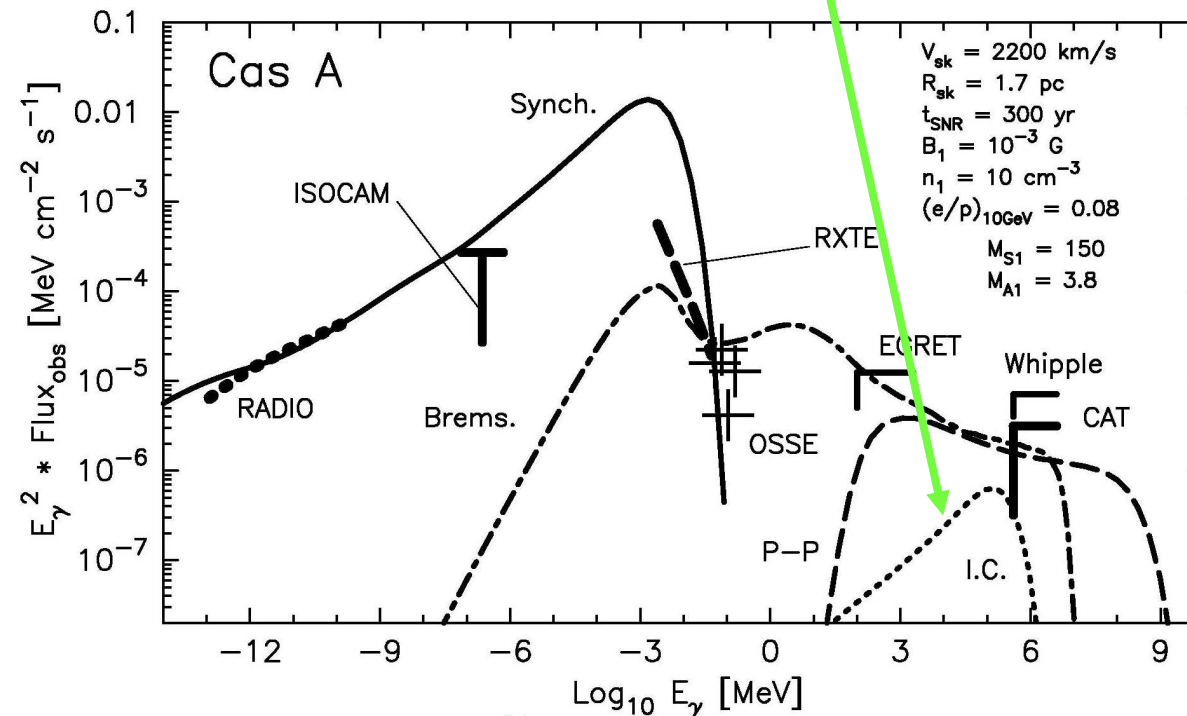


• Cosmic-Ray Acceleration in Supernova Remnants

★ e.g., Cas A

☞ Secondary Radiation Processes:

- Synchrotron Radiation
- Bremsstrahlung
- Comptonization / Inverse Compton Scattering
- Hadronic-Cascade Pion Decay



Radiation from Accelerated Charged Particles

Radiation from Accelerated Particles

★ Acceleration of Charged Particle Occurs

- ☞ In Coulomb Field of an Atomic Nucleus
- ☞ In Magnetic Fields of
 - A Neutron Star
 - Interstellar Medium

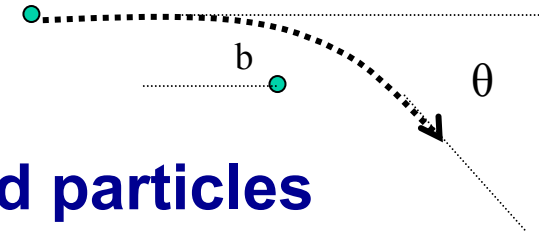
★ Radiation Characteristic Depend on

- ☞ Energy Relations between Charged Particle and Deflecting Field
- ☞ Energy of Charged Particle

★ Radiation Types

- | | |
|------------------------------|---------------------------------|
| ☞ Bremsstrahlung | Coulomb-Field Acceleration |
| ☞ Gyromagnetic Radiation | $v \ll c$ |
| ☞ Gyro-Synchrotron Radiation | $v \sim 0.1 c$ |
| ☞ Synchrotron Radiation | $v \sim c$ |
| ☞ Curvature Radiation | motion curved magnetic field |

Bremsstrahlung



★ Coulomb interaction of two charged particles

- ☞ "free-free" transitions of e^- states in the nucleus' field
- ☞ "Bremsstrahlung"
- ☞ "Free free emission"

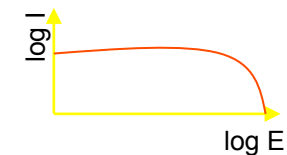
$$\tan \frac{\Theta}{2} = \frac{Ze^2}{mv^2 b}$$

★ Non-relativistic and relativistic cases

- ☞ Lorentz transformation between particle and observer frames
- ☞ Decomposition of acceleration into parallel/perpendicular to v
- ☞ Fourier analysis yields radiated spectral distribution

★ Properties:

- ☞ Flat Spectrum,
up to limiting energy transfer, exponential cutoff
- ☞ "Gaunt factor" describes target/environment-specific collision parameters
- ☞ "Thermal Bremsstrahlung" from integration over Maxwellian velocities
- ☞ Relativistic-particle Bremsstrahlung from QM treatment

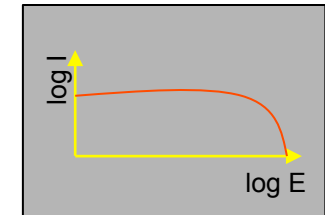
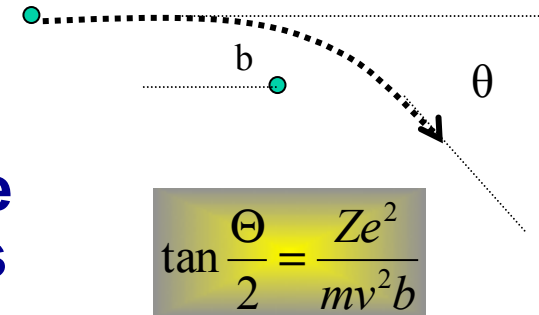


Bremsstrahlung

★ Bremsstrahlung of Deflected Charge in Coulomb Fields of Nuclei in a Gas

👉 **Radiated Spectral Power:**

$$P(\nu, \nu) d\nu = N_i \nu \frac{16Z^2 e^6}{3m^2 c^3 \nu^2} \int_{b_{\min}}^{b_{\max}} \frac{db}{b} \cdot d\nu = N_i \nu \frac{16Z^2 e^6}{3m^2 c^3 \nu^2} \cdot \ln\left(\frac{b_{\max}}{b_{\min}}\right) \cdot d\nu$$



★ Bremsstrahlung Cross Section

👉 **High-energy e⁻ on unshielded charge Ze → 'cross section':**

$$\sigma_r = 4Z^2 \frac{e^2}{\hbar c} \left(\frac{e^2}{mc^2} \right)^2 \frac{1}{\hbar \omega} \frac{1}{E_i^2} \left(E_i^2 + E_f^2 - \frac{2}{3} E_i E_f \right) \left[\ln \left(\frac{2E_i E_f}{mc^2 \hbar \omega} \right) - \frac{1}{2} \right]$$

👉 **In a plasma:**

- screening corrections
- Gaunt factor (b_{\max}/b_{\min}) encodes properly-averaged collisional parameters
- see *Bethe & Heitler (1964), Koch & Motz (1959)*

For a Maxwellian distribution of electron velocities, the spectral emission per unit volume is

$$dP_B(T)/dVdn = 6.8 \times 10^{-38} T^{-1/2} e^{-E/kT} N_e N_Z Z^2 g_B(T,E) \quad [\text{erg cm}^{-3} \text{ s}^{-1} \text{ Hz}^{-1}]$$

N_e = electron density

N_Z = ion density (charge z)

$E = h\nu$ = photon energy

$g_B(T,E)$ = Gaunt Factor, $(E/kT)^{-0.4}$ for $E \ll kT$

The total bremsstrahlung emission is:

$$dP_B(T)/dV = 1.4 \times 10^{-27} T^{1/2} N_e N_Z Z^2 g_B(T) \quad [\text{erg cm}^{-3} \text{ s}^{-1}] \quad \text{where } g_B(T) \sim 1.2$$

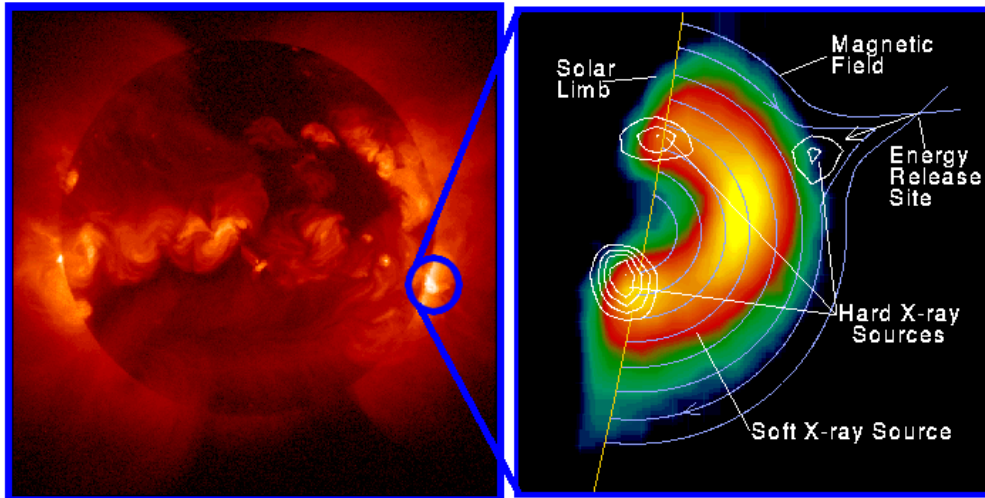
For a plasma with cosmic abundances:

$$dP_B(T)/dV = 1.4 \times 10^{-27} T^{1/2} N_e^2,$$

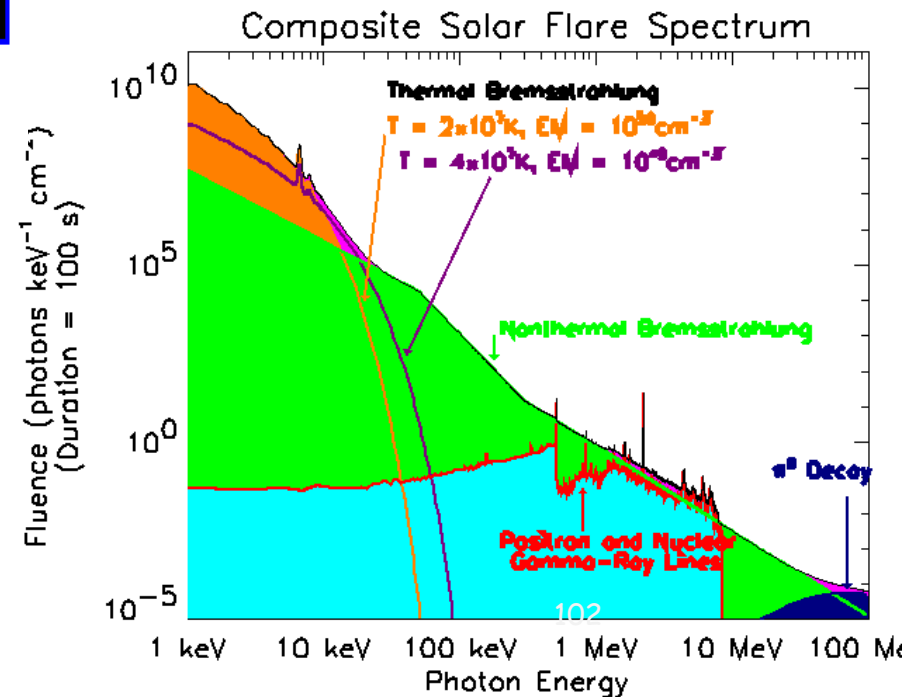
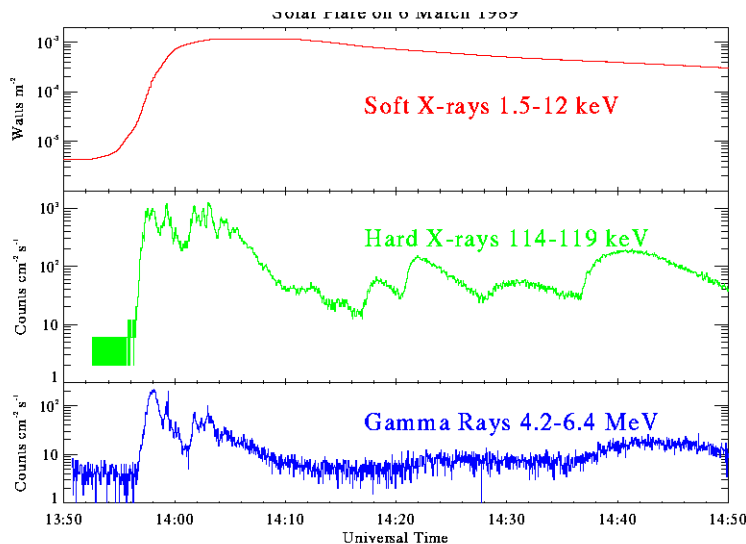
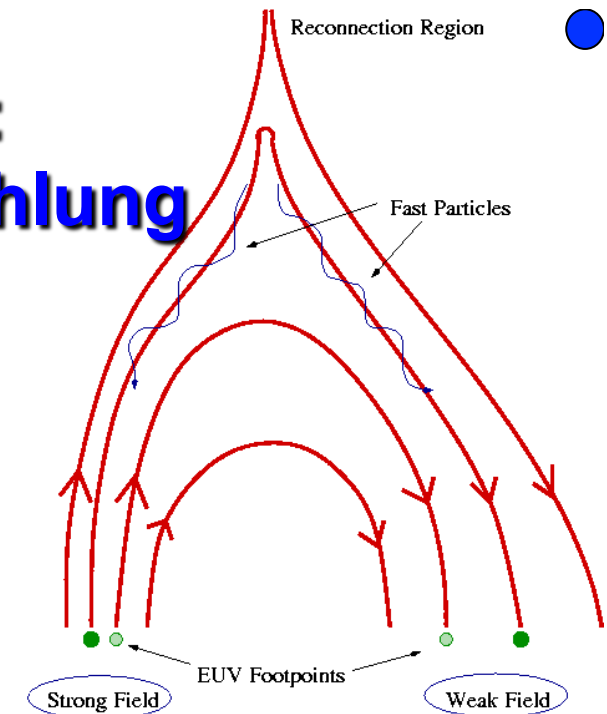
since $N_e N_Z Z^2 \sim 1.4 N_e^2$ for cosmic standard abundances

Bremsstrahlung is emitted from optically-thin thermal plasma

Typical Spectra of Solar Flare: Thermal & Non-Thermal Bremsstrahlung



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.



Synchrotron Radiation

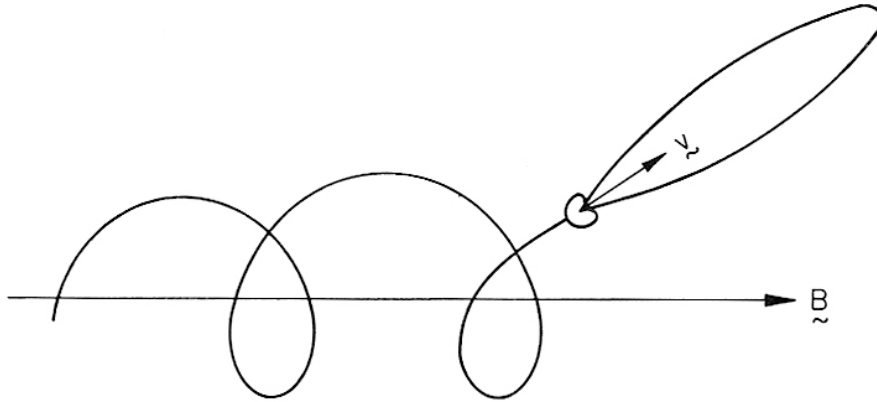


Fig. 3.2. A relativistic particle spiraling in a magnetic field emitting synchrotron radiation with the angular pattern as indicated.

Particle in magnetic field B
 -> Acceleration $\perp B$
 -> Gyration

Gyration frequency:
 $\omega = eB/\gamma mc = 1.8 \times 10^7 B \text{ g}^{-1}$
 $= 14.4 B/E \text{ [Hz]}$
 with Lorentz factor γ

Radiation Characteristics:

Power per solid angle:

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2}{4\pi c^3} \frac{\sin^2 \vartheta}{(1 - \beta \cos \vartheta)^5}$$

$b = v/c$, $\delta = \text{angle } v \leftrightarrow \text{observer}$

Radiation Cone Opening Angle:

$$\alpha = \gamma^{-1} = [1 - \beta^2]^{1/2} = \frac{mc^2}{E} = 8.2 \cdot 10^{-7} E^{-1} \text{ rad}$$

Radiation Spectrum of a
 Pulse Sweeping by an Observer:

$$2\pi \nu_{crit} = \frac{c\beta}{\rho} \approx 6 \cdot 10^{28} \frac{E^3}{\rho} \text{ Hz}$$

(e^- gyrating with orbit radius r) or expressed as
 (with ψ pitch angle $B-v$) -> $g > 10^3$ for X/ γ rays!

$$\nu_{crit} \approx 6.3 \cdot 10^{18} \sin \psi \frac{B}{\mu G} \frac{E^2}{\text{GeV}^2} \text{ Hz}$$

Total Power of Synchrotron Radiation ($a \parallel v$):

$$P_{\parallel} = \frac{2e^2}{3c^3} \dot{v}^2 \gamma^6$$

Spectra from Cosmic Sources with Radiating e^-

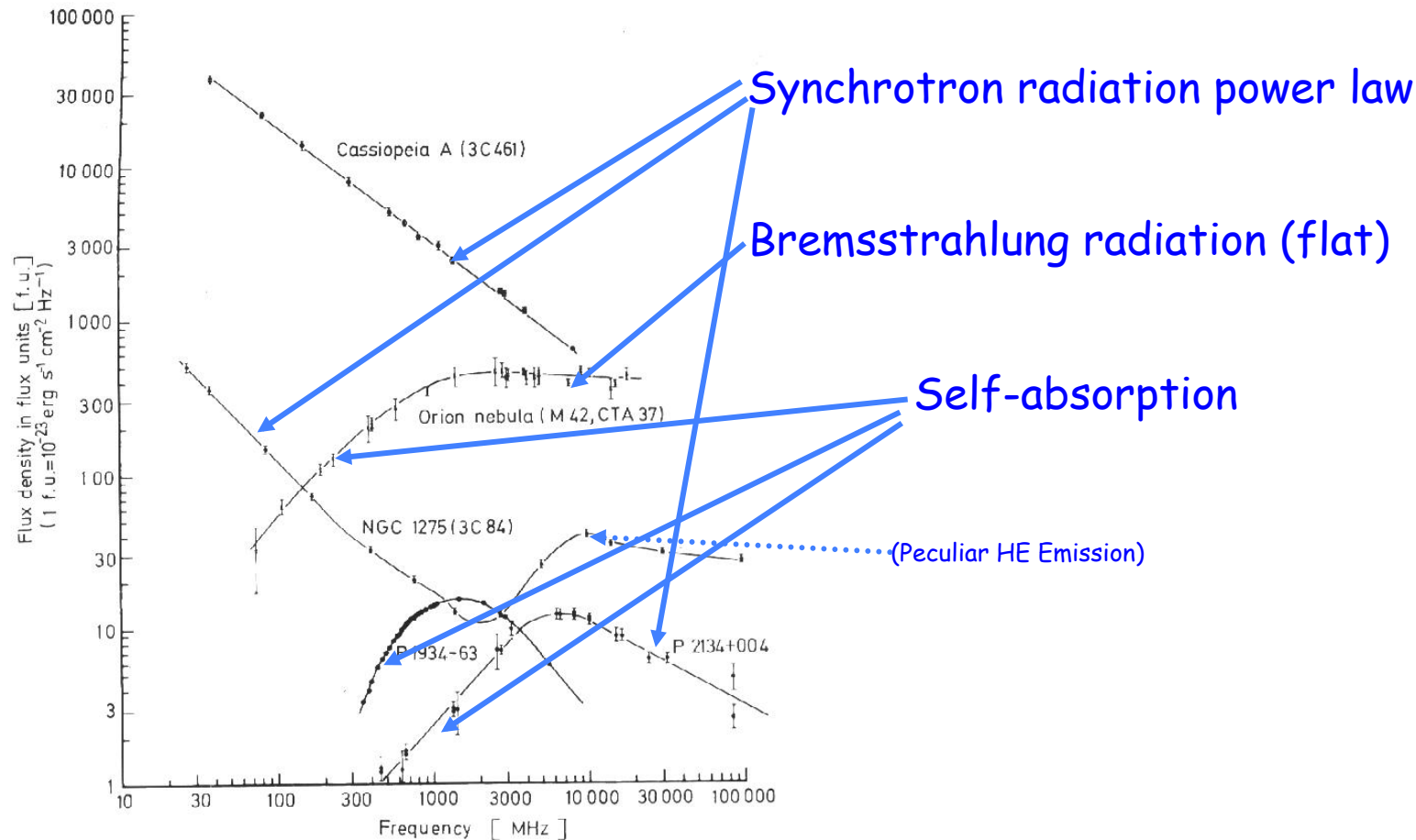


Fig. 1.4. Radiofrequency spectra of sources exhibiting the power law spectrum of synchrotron radiation (Cassiopeia A), the flat spectrum of thermal bremsstrahlung radiation with low frequency self absorption (Orion Nebula), unusual high frequency radiation (NGC 1275), and low frequency absorption processes (P1934 – 63 and P2134 + 004). The data for P2134+004 are from E. K. Conklin, and the other data are from Kellermann [1966], Hjellming, and Churchwell [1969], Terzian and Parrish [1970], and Kellermann, Pauliny-Toth, and Williams [1969].

Atomic Transitions

Characteristic X-rays

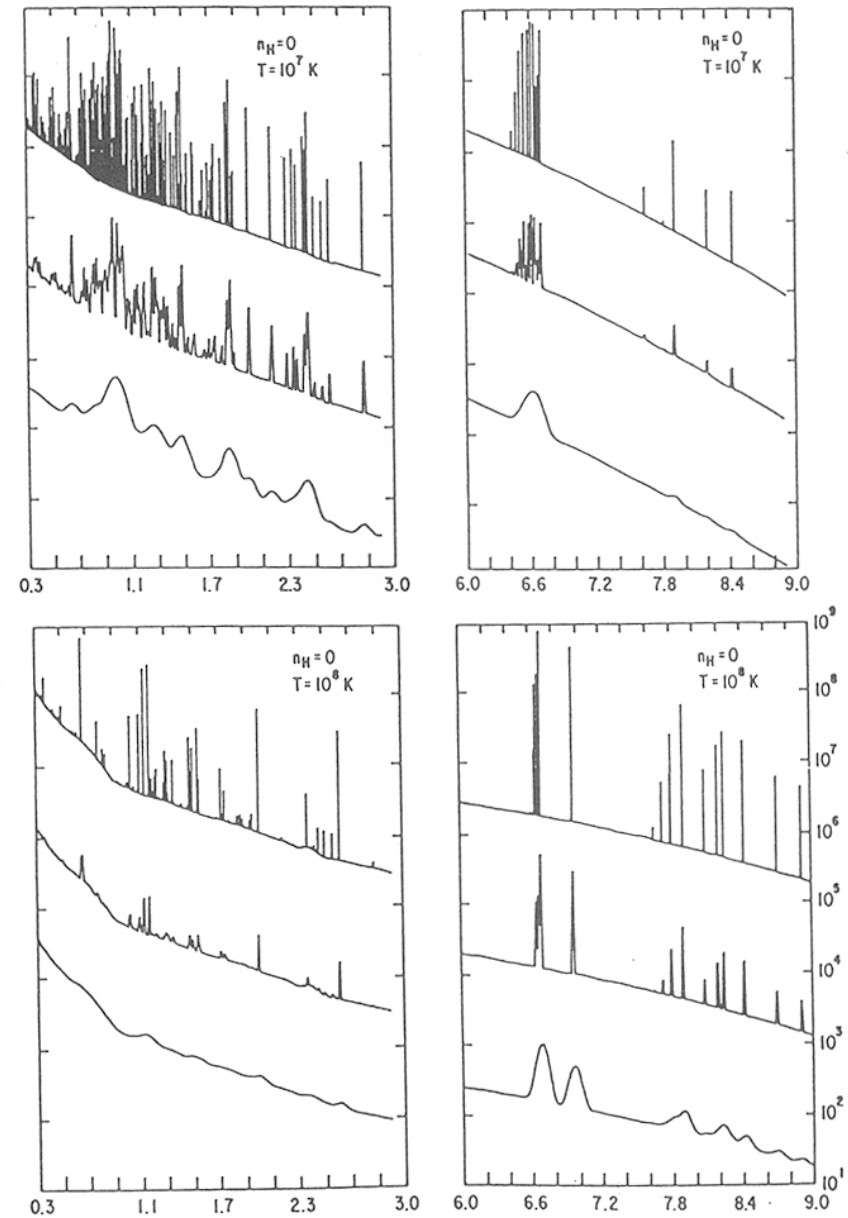
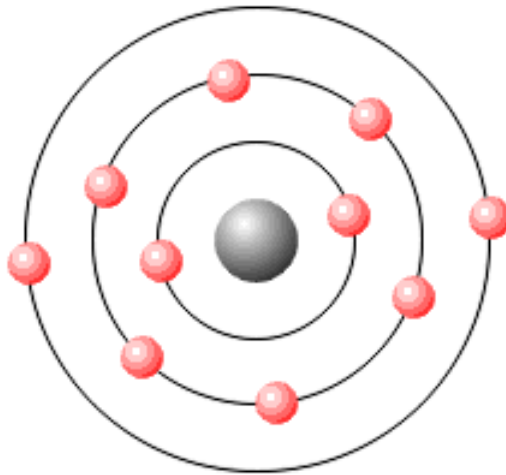


Figure 3. Coronal equilibrium spectra (arbitrary logarithmic intensity) of plasmas with solar abundances, in the energy bands (keV) containing Fe L- and Fe K-emission, as viewed with detectors having FWHM resolutions of 1, 10 and 100 eV (upper, middle and lower trace of each panel).

Emission from Supernova Remnants

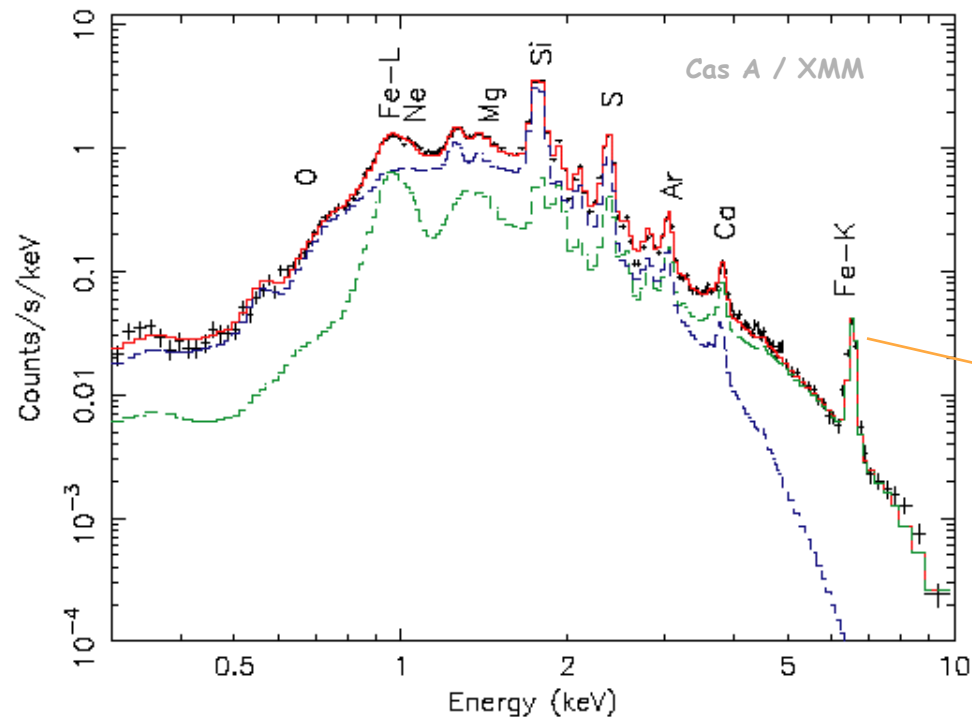


Fig. 2. An example of a spectral fit within a single $20'' \times 20''$ pixel – cool component in blue, hot component in green and full model in red.

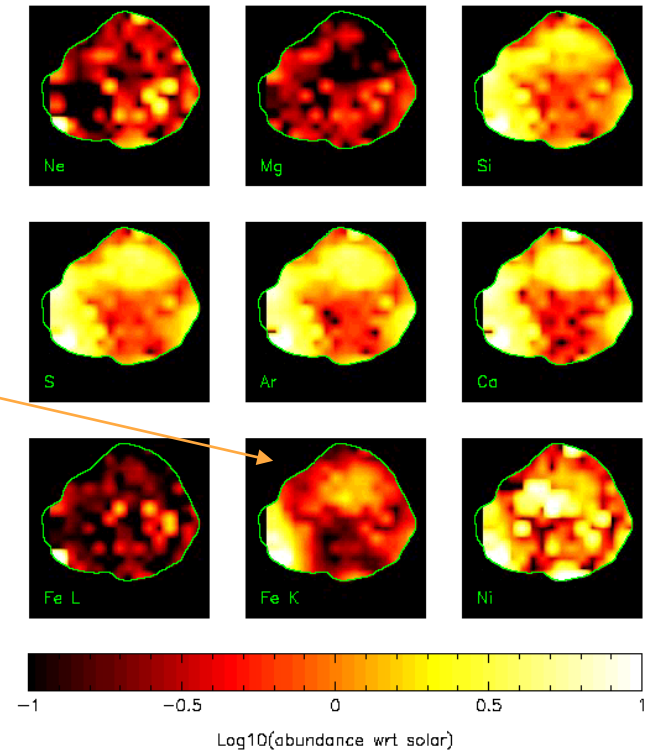


Fig. 5. Abundance maps for the elements included in the spectral fitting. All are plotted on the logarithmic scale indicated by the bar at the bottom.

- SN Material (and Swept-Up Material) Recombination Lines
- + Hot Cavity Thermal Radiation

Nuclear Transitions

Nuclear De-Excitation



- Cosmic-Ray Collisions with ISM Gas Excite Nuclei
- De-Excitation Leads to Characteristic Gamma-Ray Emission

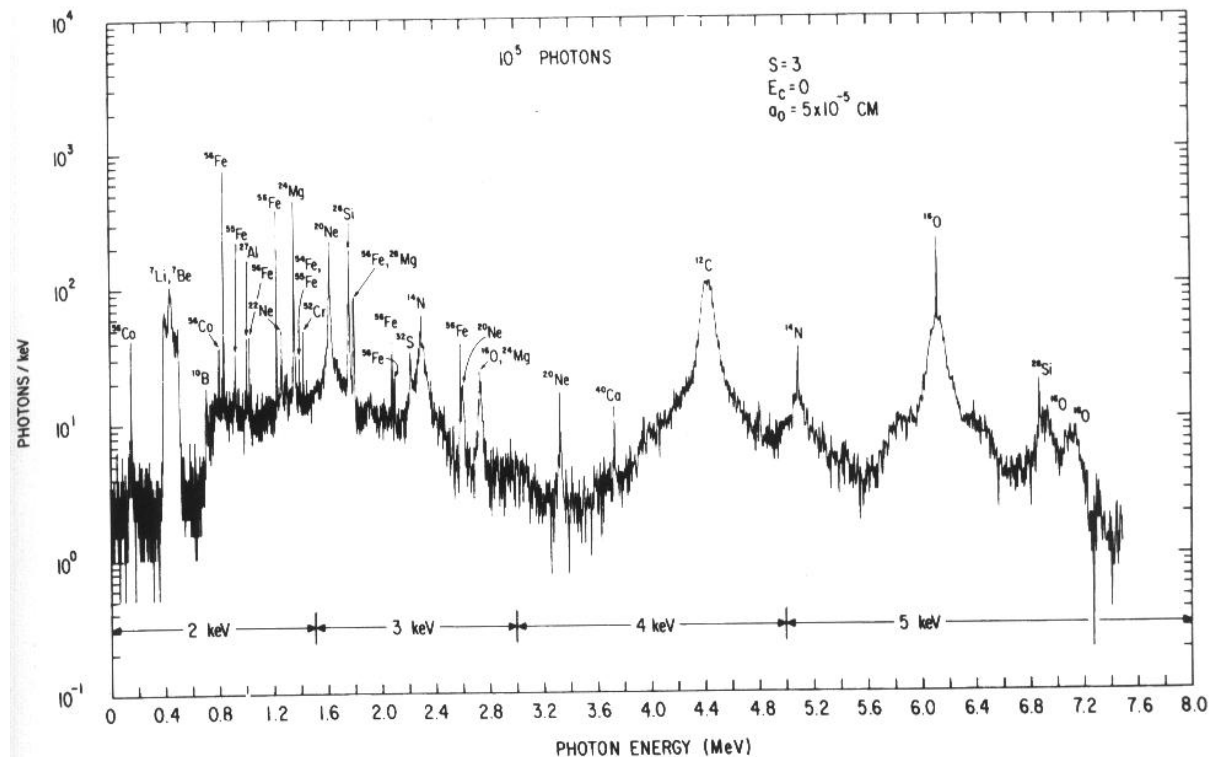
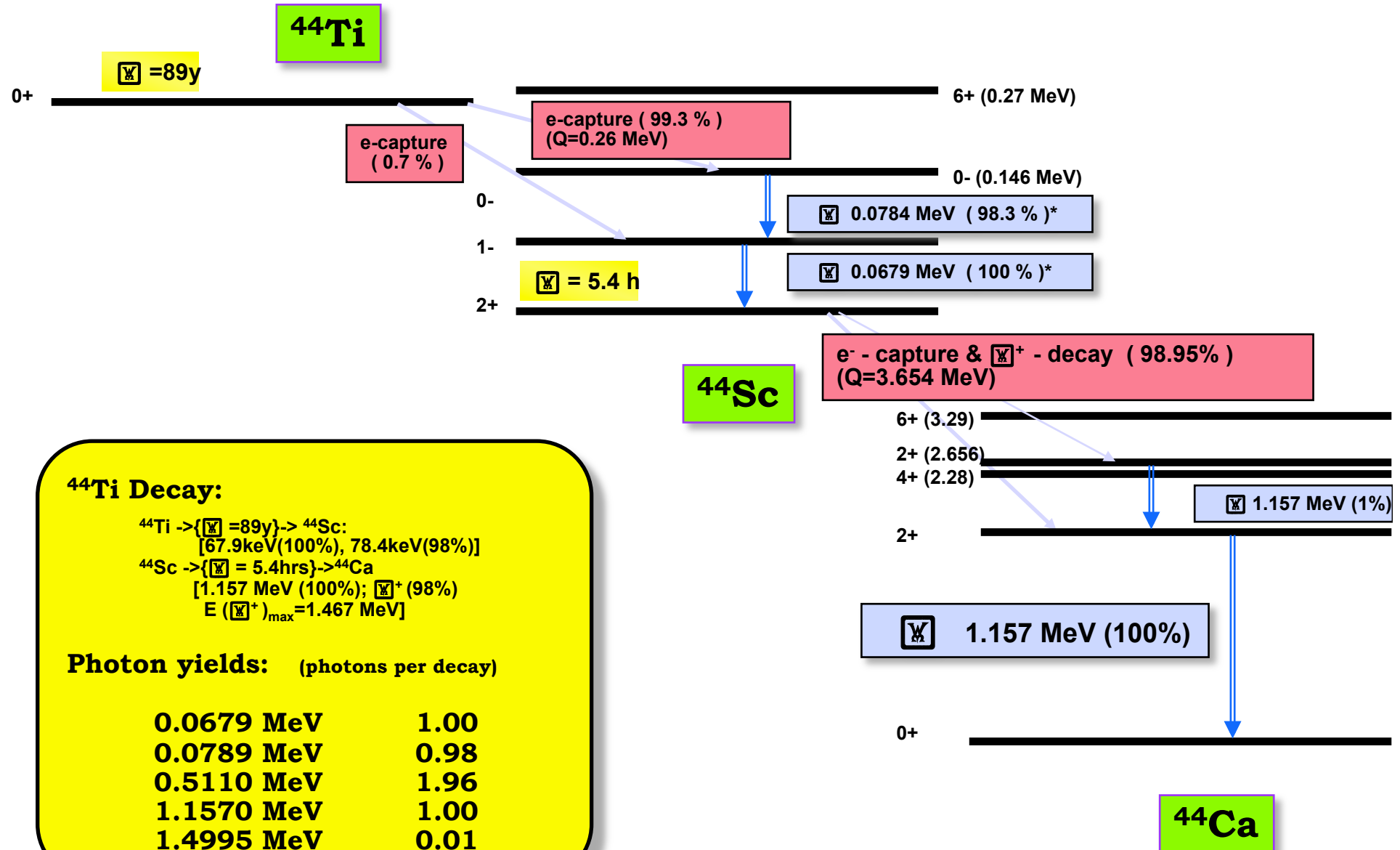
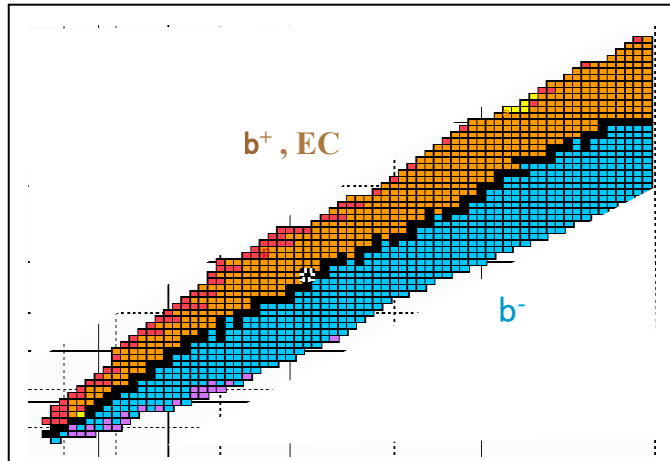


Fig. 5.12. Calculated γ -ray spectrum from energetic particles and ambient medium having solar composition. The energetic particles obey a power law spectrum in kinetic energy with spectral index s above a low-energy cutoff E_c , and the contribution from lines from interstellar grains of characteristic radius a_0 is included. From Ramaty et al. (1979 [419])

^{44}Ti Decay



Gamma-Rays from Radio-Isotopes

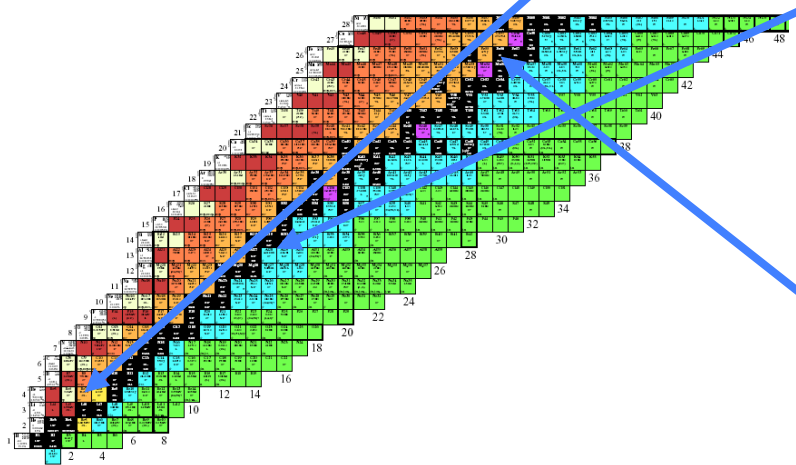


- Nucleosynthesis Reactions Produce Isotopes on Proton- and Neutron-Rich Sides of "Valley of Stability"

☞ Radioactive Decays

- β^- decay, electron capture
- β^+ decay

- 511 keV, ${}^7\text{Be}$ \rightarrow Novae
 \rightarrow p-Captures, β^+ Decays
 \rightarrow ${}^{19}\text{F}$ Production...
- ${}^{26}\text{Al}$ \rightarrow Reaction Path Details in Stars/
 SNe, n-Process
 \rightarrow Metal/Fe Ratio, Si/Fe
- ${}^{44}\text{Ti}$, ${}^{56}\text{Ni}$ \rightarrow Most Stable Isotopes ${}^{56}\text{Ni}/{}^4\text{He}$,
 Freeze-Out of NSE
 \rightarrow Metal/Fe Ratio, Heavies/Fe



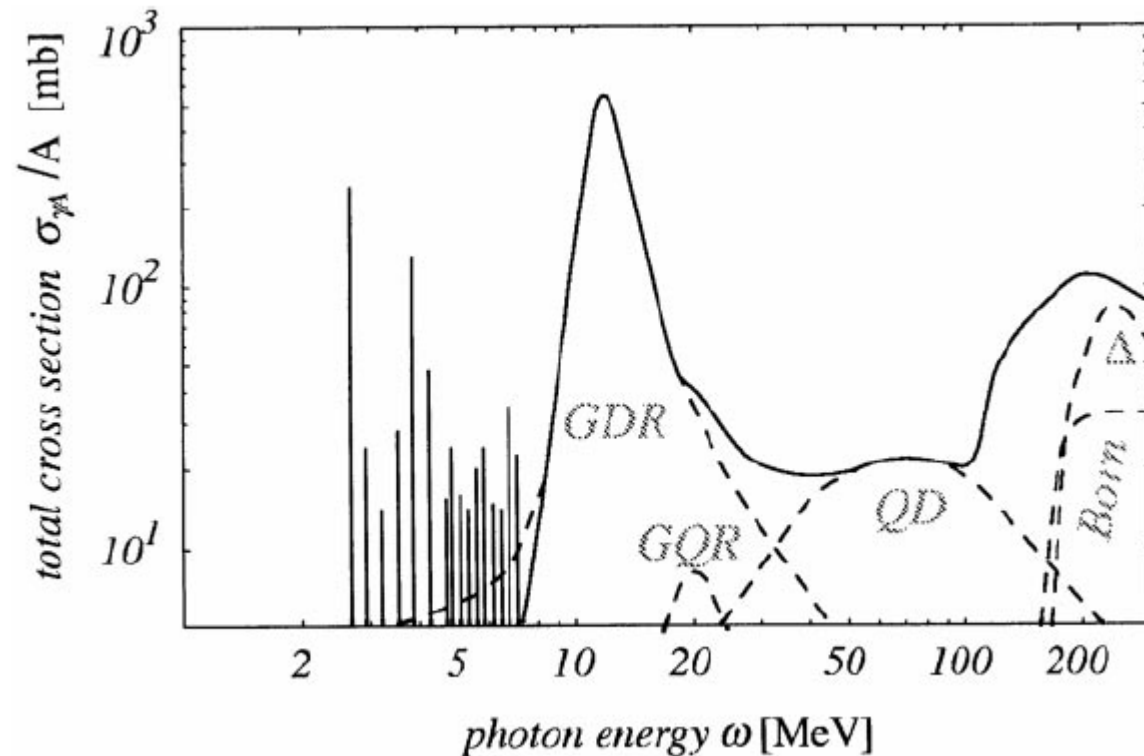
Nucleosynthesis Study with Gamma-Ray Lines



- Radioactive Trace Isotopes are Nucleosynthesis By-Products
- For Gamma-Spectroscopy We Need:
 - ☞ Decay Time > Source Dilution Time
 - ☞ Yields > Instrumental Sensitivities

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^7Be	77 d	$^7\text{Be} \rightarrow ^7\text{Li}^*$	478
^{56}Ni	111 d	$^{56}\text{Ni} \rightarrow ^{56}\text{Co}^* \rightarrow ^{56}\text{Fe}^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}\text{Co} \rightarrow ^{57}\text{Fe}^*$	122
^{22}Na	3.8 y	$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+$	1275
^{44}Ti	85 y	$^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$	78, 68; 1157
^{26}Al	$1.04 \cdot 10^6 \text{y}$	$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$	1809
^{60}Fe	$3.x \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
e^+	$\dots \cdot 10^5 \text{y}$	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma..$	511, <511

States of Nuclei and their Components



★ **We See Effects of** (with increasing energy):

- ☞ **Excitation of Single Nucleons in Nucleus Potential ("Nuclear Lines")**
 - $h\nu = E_{\text{nuc}}$
- ☞ **Collective Excitations of Nucleon Groups ("Pygmi/Giant Resonances")**
 - giant resonances: protons versus neutrons
 - quasi-deuteron resonances: a pair of proton and neutron
 - each of these occur in all multipole orders
- ☞ **Excitations of Single Nucleons ("Delta Resonance")**
- ☞ **...-> Hadron/Quark Phase Transitions**

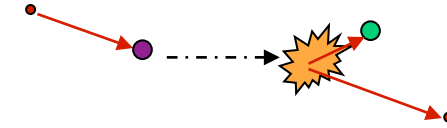
★ Particle-Antiparticle Annihilation



Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions

☆ e.g. $^{12}\text{C}(p,pn)^{11}\text{C}(b^+)$, or $^{16}\text{O}(p,a)^{13}\text{N}(b^+)$



☆ Pion Production in HE Collisions

$$p + p \rightarrow p^+ + X$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu & (\tau = 2,6 \cdot 10^{-8} \text{ s}) \\ &\downarrow \rightarrow e^+ + \nu_e + \bar{\nu}_\mu & (\tau = 2,2 \cdot 10^{-6} \text{ s}) \end{aligned}$$

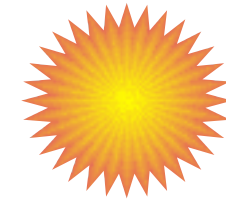
✓ Hot-Plasma Pair Production

☆ 'kT>MeV'-Plasma

☞ Accretion Columns & Disks

☞ Jet Bases

$$g + g \rightarrow e^+ + e^-$$



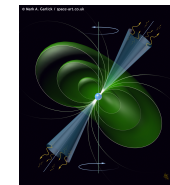
✓ E.M.-Cascade Pair Production

☆ Strong Magnetic Fields

☞ Pulsars

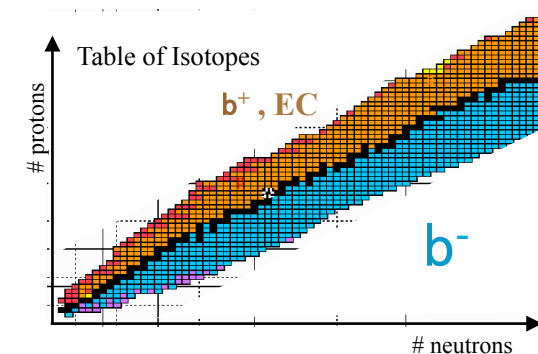
☞ Jets

$$g + B \rightarrow e^+ + e^-$$



✓ Nucleosynthesis

☆ e.g. $^{56}\text{Ni}(b^+)$, $^{44}\text{Ti}(b^+)$, $^{26}\text{Al}(b^+)$, $^{22}\text{Na}(b^+)$,
 $^{13}\text{N}(b^+)$, $^{14}\text{O}(b^+)$, $^{15}\text{O}(b^+)$, $^{18}\text{F}(b^+)$



Known Sources of Positrons, E_{e^+}

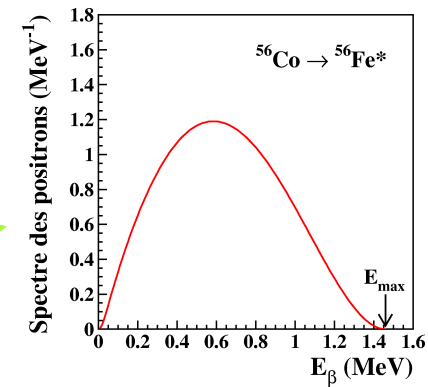
- Radioactive Nuclei

- ★ Sources:

Supernovae, Novae,
Cosmic Rays & ISM

- ★ Positron Energies:

~MeV



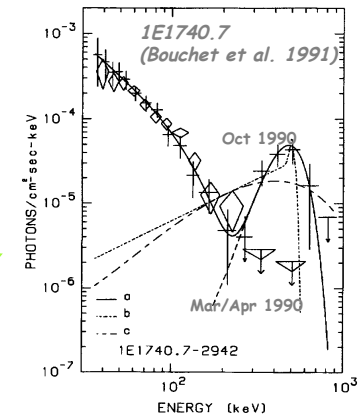
- Pion Production

- ★ Sources:

Cosmic Rays & ISM

- ★ Positron Energies:

$\langle E \rangle \sim 30$ MeV (MeV...GeV)



- Pairs from Hot Plasma

- ★ Sources:

Accreting Binaries

- ★ Positron Energies:

~MeV $T > 100$ keV ($E_{\text{thr}} = 1.02$ MeV)

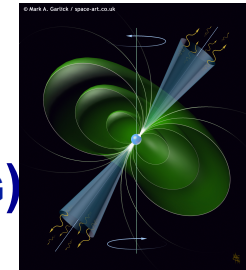
- Pairs from Strong Magnetic Fields

- ★ Sources:

Pulsars, Magnetars

- ★ Positron Energies:

~MeV...GeV ($E_{\text{thr}} = 1.02$ MeV $B > 10^{12}$ G)



★ Pion Decay: Hadronic HE-Processes

Pion Decay

- Pions are Unstable Mesons $q\bar{q}$ and Decay

👉 $p^+ \leftarrow u\bar{d}$

👉 $p^- \leftarrow \bar{u}d$

👉 $p^0 =$
mixed p - p^+

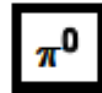
👉 $p^0 = p\bar{0}$

👉 \rightarrow

👉 **Most-Likely
Decay:**

gg

👉 $E_g \sim 67.5 \text{ MeV}$



$$J^{PC} = 1^-(0^+)$$

Mass $m = 134.9766 \pm 0.0006 \text{ MeV}$ ($S = 1.1$)

$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005 \text{ MeV}$

Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17} \text{ s}$ ($S = 3.0$)

$c\tau = 25.1 \text{ nm}$

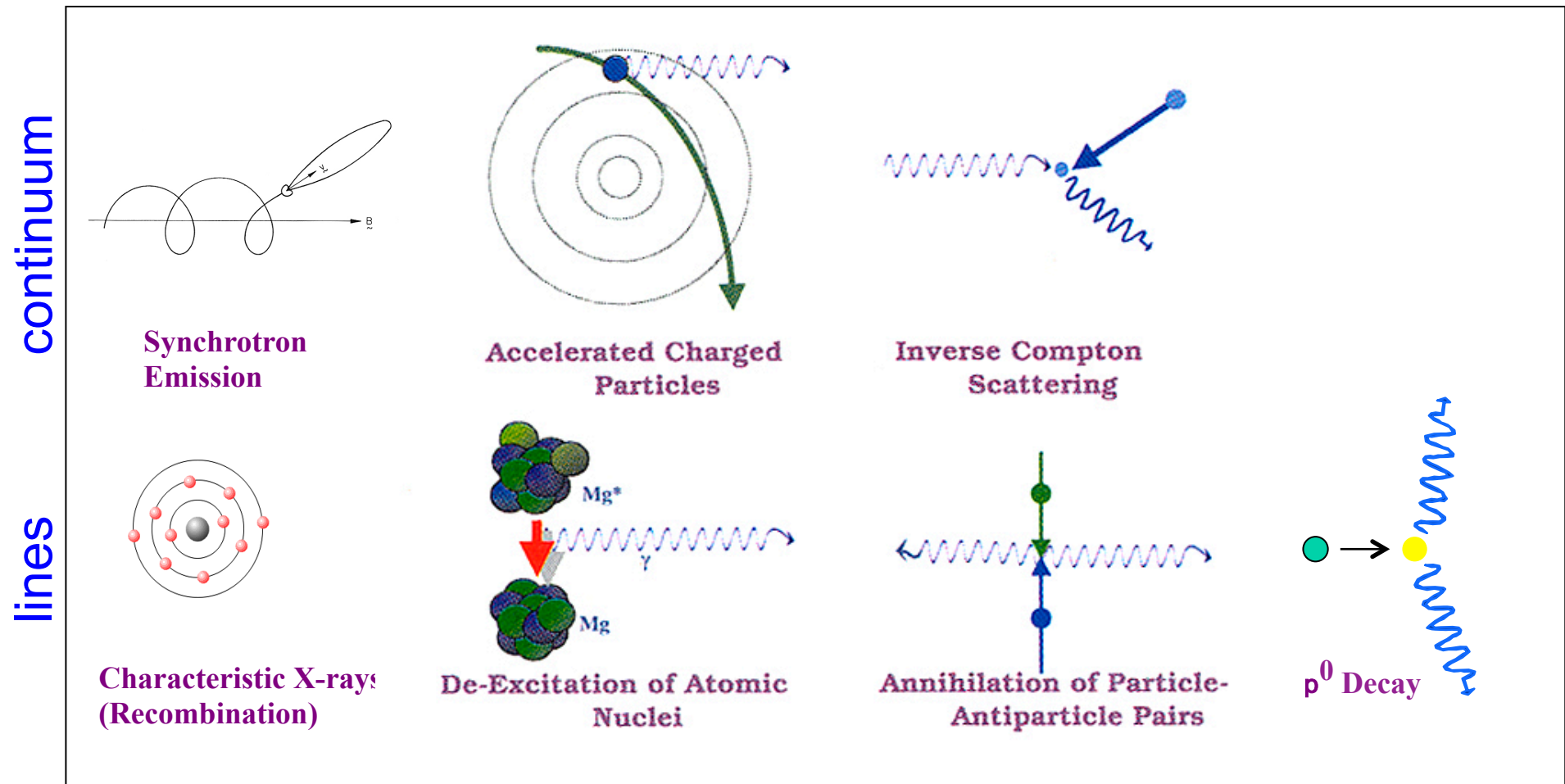
For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

π^0 DECAY MODES

	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	$(98.798 \pm 0.032) \%$	$S=1.1$	67
$e^+e^-\gamma$	$(1.198 \pm 0.032) \%$	$S=1.1$	67
γ positronium	$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$	$(3.14 \pm 0.30) \times 10^{-5}$		67
e^+e^-	$(6.2 \pm 0.5) \times 10^{-8}$		67
4γ	< 2	$\times 10^{-8}$ CL=90%	67
$\nu\bar{\nu}$	$[e] < 2.7$	$\times 10^{-7}$ CL=90%	67
$\nu_e\bar{\nu}_e$	< 1.7	$\times 10^{-6}$ CL=90%	67
$\nu_\mu\bar{\nu}_\mu$	< 1.6	$\times 10^{-6}$ CL=90%	67
$\nu_\tau\bar{\nu}_\tau$	< 2.1	$\times 10^{-6}$ CL=90%	67
$\gamma\nu\bar{\nu}$	< 6	$\times 10^{-4}$ CL=90%	67

- **Thermal Radiation**
- **Radiation from (Accelerated) Charges**
 - ★ **Bremsstrahlung**
 - ★ **Synchrotron Radiation**
 - ★ **Curvature Radiation**
- **Electron - Photon Scattering**
 - ★ **Thompson Scattering**
 - ★ **Compton Scattering**
- **Transitions in QM Systems**
 - ★ **Atomic Transitions**
 - ★ **Nuclear Transitions**
- **Positron Annihilation**
- **Pion Decay**
- **...**

HE Astrophysics: Basic Radiation Mechanisms



Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?

★ Characteristic Nuclear Radiation

- Nuclear Excitation Lines
- Radioactive Decay

Relativistic Particle Acceleration → CRs

- Solar Flares
- Interstellar Shocks
- AGN

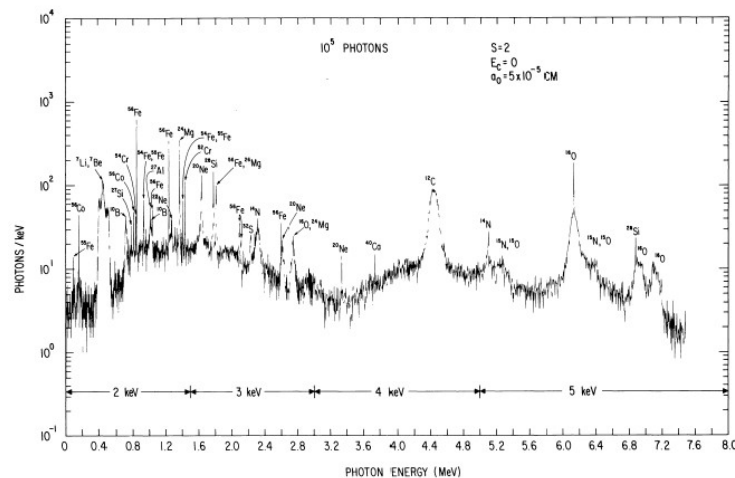


FIG. 18.—Monte Carlo simulated γ -ray spectrum for energetic particles and ambient medium having solar compositions; s and E_0 are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

Current Nucleosynthesis Source Locations

